JIMMA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
JIMMA INSTITUTE OF TECHNOLOGY
FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING
STRUCTURAL ENGINEERING STREAM

Effect of Staircase on Earthquake Response of Medium Rise Moment Resisting Frame Building Using Response Spectrum Analysis

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

By:
Naol Getachew Nemera

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EFFECT OF STAIRCASE ON EARTHQUAKE RESPONSE OF MEDIUM RISE MOMENT RESISTING FRAME BUILDING USING RESPONSE SPECTRUM ANALYSIS

NAOL GETACHEW NEMERA

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DECLARATION

I declare that this thesis titled "Effect of Staircase on Earthquake Response of Medium Rise Moment Resisting Frame Building Using Response Spectrum Analysis" is an authentic record of my work and has not been submitted before for degree to any other University that complies with the regulation of the University.

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ABSTRACT

Moment resisting frame (MRF) buildings have mainly two structural systems. These are primary structural system (beam and column) which resists all lateral load by frame action and secondary structural systems (staircase and walls) which are designed mainly for non-seismic forces. Even though structural modeling mostly does not include a staircase, it significantly contributes to the seismic response of the building by attracting rigidity center. The staircase acts as an inclined shear wall or as a different bracing system on either side based on its type.

The objective of the study was to evaluate the effect of a staircase on earthquake response of medium-rise MRF building using Response Spectrum Analysis. Adama town was selected as a study area since it is located in the great rift valley of Ethiopia which is characterized by a high seismic zone. The specific objectives were to evaluate the effect of staircase location, staircase type, and staircase orientation on the seismic response of regular and irregular plan buildings. The core methodology of the research was carried out by modeling and analysis of building with staircase and without staircase on ETABS V.18 to investigate seismic effect of selected staircase types. The four staircase types considered in this study are, straight flight with no landing, doglegged, L-shaped, and U-shaped staircases. The study was done on 8-story MRF building with a regular and irregular plan. In this study staircases were provided at the center and corner of the building. Response spectrum analysis was used as seismic analysis method according to ES EN, 2015 code.

According to analyses result based on lateral story displacement, story drift, base shear, base overturning moment, story stiffness, and eccentricity, staircases has significant effects on seismic response of buildings. The staircases provided at the center of regular and irregular building positively contributes to the story stiffness ranges from 3.48% to 28.86%. The effect is negative on stiffness of regular and irregular building having a staircase at the corner up to 7.96%. Doglegged staircase type less affects seismic responses of buildings as compared to other types of a staircase and best alternative to be provided at a corner of the building. The L-shaped staircase was the best alternative to be provided at the center of both regular and irregular buildings because it has a maximum and uniform seismic performance in both X and Y-directions. A straight staircase was orientation sensitive and it more resists seismic action in the longitudinal direction as diagonal bracing than in the in-plane direction.

***Key words**: Staircase; Earthquake; RSA; Displacement; Drift; Base shear; Stiffness*

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TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

- CQC: -Complete Quadratic Combination
- DCM: - Medium Ductility Class.
- DCH: - High Ductility Class.
- ES EN: - Ethiopian Standard based on European Norm.
- ETABS: - Extended 3D Analysis of building System; Software program used for structural analysis and design of building.
- G1: - regular and irregular building modeled without staircase
- G2: - Regular building modeled with staircase at center
- G3: - Regular building Modeled with staircase at corner
- G4: - Irregular building modeled with staircase at center
- G5: - Irregular building modeled with staircase at corner
- MER: - Main Ethiopian Rift; a valley that runs through Ethiopia in southwest direction from afar triple junction and characterized by high seismic hazard
- MRF: - Moment Resisting Frame; type of structural system which resist force by frame action connected with rigid joint.
- NEHRP: - National Earthquake Hazard Reduction Program
- PGA: - Peak Ground Acceleration; the ration of maximum ground acceleration during earthquake to gravitational acceleration.
- RC: - Reinforced Concrete
- RSA: - Response Spectrum Analysis.
- S1: - Straight flight staircase with no landing
- S2: - 180^{O} turning staircase with one landing (Doglegged staircase)
- S3: - 90^{O} turning staircase with one landing (L-Shaped Staircase)
- S4: -180^{O} turning staircase with two landing (U-Shaped staircase)

CHAPTER ONE
INTRODUCTION

1.1. Background of the Study

The earthquake is a spontaneous event and behaves very differently. The force generated by the earthquake's seismic action is different from other types of loads such as gravity and wind. It hits the weakest point in the entire three-dimensional building. Poor construction quality leads to many structural weaknesses thus causing serious ones. Secondary structural elements contribute to the damage related to earthquake unless properly considered during design of building structures.(Khadse and Khedikar, 2018)

A staircase is mostly provided at the position where it most suits the functional purpose of the building. Sometimes this location affects the structural response of the building against seismic action by attracting rigidity center toward itself beside causes torsion. These influences of the staircase are not so significant in steel structures due to joint connections between columns and middle-story beams. But there may be a high possibility of the plastic joint formation near the staircase in concrete structures.

Moment Resisting Frame (MRF) is a type of structural system which resists all vertical and lateral load primely by bending of beams and columns as well as by rigid connection between these frame elements. Evaluation of the effect of staircase parameters (location, type, and orientation) on seismic response of Moment resisting frame building is very important to properly distribute the earthquake-induced lateral force throughout the entire structures. Knowing the extent to which the staircase affects the seismic response of a structure is crucial to reduce the possible structural damage caused by earthquake excitation. The effect of plan irregularity on seismic response is required to be integrated with a seismic response of stairs.

Earthquake is the main source of seismic action and its magnitude depends on peak ground acceleration (PGA) coefficient. The study area of this research is located in main rift valley of Ethiopia which is characterized by high seismic coefficient. A number of earthquakes have shaken the Main Ethiopian Rift (MER), and the Southern Rift Valley of Ethiopia recently between 2005 and now taking the risk of seismic hazard to the head. It is expected that property damage and loss of human life due to seismic risk will increase significantly, because now a days it coincides with a notable construction of infrastructure in the main regions of the country.(Khadse and Khedikar, 2018)

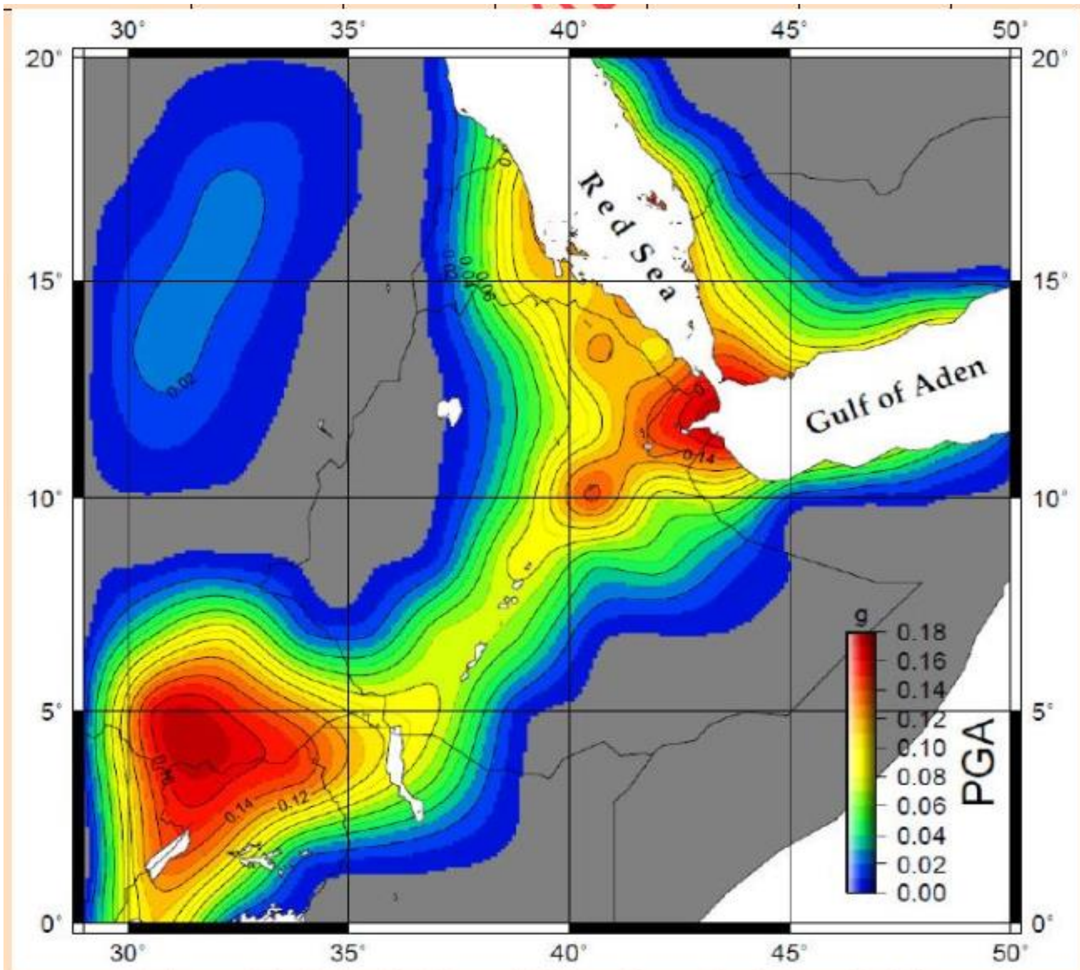


Figure 1.1: Seismic hazard map along the horn of Africa (ES EN 1998-1:2015)

1.2. Statement of the Problem

Mostly staircase is overlooked to be modeled as an integral part of MRF building during 3D analysis. but they significantly contribute to the seismic response due to lateral loads. many Architects provide a staircase from the perspective of the functional purpose of the building and structural engineers design it for gravity loads. Specially location, type, orientation, and support condition of staircases have a significant effect on the seismic response of the structure by changing rigidity center and causes stiffness irregularity.

Since earthquake force is an unprecedented type of lateral force, every structural system should be designed in such a way that it best resist collapse in high seismic region. Special attention shall be given to the seismic design of structures located in rift valley because of the higher seismic coefficient in these regions. One of the towns located in the great rift valley of Ethiopia taken as the study area for this research is Adama town. The town is located in seismic zone 4. (ES EN 1998-1: 2015).

Earthquake damage generally begins at locations of structural weaknesses in multi-story frame buildings. Buildings with openings in slabs are subject to damage due to the action of lateral loads. Floor and ceiling systems act as horizontal diaphragms in building structures.(Arya V Manmathan and Aiswarya S, 2017)

Past studies show that the vulnerability of the staircase element, when subjected to the earthquake as it imparts additional stiffness to the building. For these reasons the elements that constitute the stair are often characterized by high seismic demand. This develops more shear force at short columns and can lead to a premature brittle failure.(Danish *et al.*, 2013)

Generally, new research is required to investigate seismic response effects of most common and widely used staircase types at different location in the building. if staircase is not properly analyzed and designed along with other primary structures (column, beam and slab) for seismic excitation it may cause shifting of rigidity center and expose columns nearby the stair to attraction higher shear force and finally the structure will unable to safely transfer the lateral seismic excitations. Furthermore, different staircase types have unique response behavior under seismic excitation. To avoid these problems related to structural performance and behavior of staircase in building, the effects of staircase on the seismic response of RC building have to be examined.

1.3. Research Question

The study intended answer the following question:

1. What is the effect of a staircase on the seismic response of reinforced concrete MRF building structures?
2. What is seismic impact of staircase location on reinforced concrete MRF building?

3. What type of staircase has higher impact on seismic response of MRF building?
4. How staircase orientation affects the seismic behavior of MRF building?
5. What is the possible best layout and structural configuration of a staircase for a regular and irregular buildings to contribute to the performance of structures against seismic excitations?

1.4. Objective of the Study

1.4.1. General Objective

Study aimed to evaluate the effect of a staircase on earthquake response of medium-rise moment resisting frame (MRF) building using response spectrum analysis.

1.4.2. Specific Objective

- ❖ To investigate the effect of staircase location on earthquake response of reinforced concrete MRF building and recommending the appropriate location to provide stairs for higher seismic performance in high seismic region.
- ❖ To investigate the effect of staircase type on earthquake response of MRF building and to recommend the appropriate type of stairs for a regular and irregular building to enhance the staircase to contribute to the performance of building against seismic demand.
- ❖ To investigate the effect of orientation of stairs on earthquake performance of MRF building and possible behavior of the stairs in orthogonal directions during seismic action.
- ❖ To integrate the effect of plan irregularity with the effect of a staircase on the seismic response of the building.
- ❖ To investigate best staircase layout for a regular and irregular buildings to contribute to the performance of buildings and minimize seismic impact of staircases.

1.5. Significance of the Study

The result of this study is expected to provide input of guidance on proper utilization of stairs so that it can best contribute to lateral force resistance of reinforced concrete MRF buildings.

Additionally, it is useful to reduce the failure of building structures under seismic load due to shifting of the center of rigidity caused by improper utilization of the staircase. This besides reduces the amount of seismic action to be resisted by especial lateral load resisting structures such as shear wall and bracing members. It will also contribute to change the building cost by reducing the extent of special structures required to act against earthquake forces.

The study will help educational institutions and students to get an insight into the role of a staircase in lateral load resistance in addition to gravity loads and to conduct further study. It also helps students to give special attention to the architectural and structural design of the staircase like other primary structural members such as beams and columns.

1.6. Scope and Limitation of the Study

The scope of the study is limited to reinforced concrete Moment Resisting Frame (MRF) building that resists all lateral force by frame action. Since MRF structures are designed in such a way that beams and columns resist all vertical and lateral load by rigid connection, elevation shaft was not included in the analysis. The grade of materials is C20/25 concrete grade and S-300 reinforcing steel grade. the study will not cover variation in building height and limited to medium-rise buildings with 8-stories. The functional classification of the building is mixed-use. The staircase material is also limited to reinforced concrete having the same grade as other primary structural members.

The source of seismic action to be considered in the analysis is earthquake-induced seismic action as provided by the design code mentioned and does not include other types of lateral load sources like wind load. The direction of seismic force is also limited to horizontal seismic excitation. The study area is Adama town. Because it is located in seismic hazard zone 4 according to seismic hazard zonation which helps the study to consider maximum relatively peak ground acceleration (PGA) coefficient. The study not included the design of structural members but limited to analysis of the models to evaluate the effect of a staircase on seismic response of the structure in terms of story disablement, story drift, base shear, base overturning moment, story stiffness, and eccentricity. Also, the study is limited to the following four types of straight flight staircase and will not include spiral flight stairs. staircase dimension is constant in all modeling.

i. Straight staircase with no landing,

ii. 180^o turn with one landing (Dogleg) staircase

iii. 90^o turn with one landing (L-shape) staircase

iv. and 180^o turn with two landing (U-shape) staircase

CHAPTER TWO
REVIEW OF RELATED LITERATURE

Past studies show that the vulnerability of the staircase element, when subjected to the earthquake as it imparts additional stiffness to the building, for these reasons the elements associated with the staircases are often characterized by high seismic demand. Many researchers made an investigation on the effect of an earthquake on the seismic performance of building with a variety of heights. According to the location of the investigation of the staircase largely affect the seismic response of building structures. Plan irregularity affects the safe transfer of lateral force due to unsymmetrical distribution of the forces and shifting rigidity center. So, attention should be given while providing a staircase in a building especially those with an irregular plan. Under this section, a related investigation by many authors will be presented from a different perspective to be a good background for the study so that the research gap will be identified.

2.1. Review of literatures

An important part of the staircase effects on the seismic behavior of buildings is related to the geometry of the architectural and structural plan. Three main variables can be examined, including the number of structural panels, the dimension of the stair frame, and the position of the staircase in the building. Since the span of the stair frame is usually shorter than other frames, a concentration of rigidity is created due to the shorter length of this beam. This is very important with single field structures and especially with moment frames. When the staircase is connected to the structure, it acts as a structural element. Due to the inclined shape, it acts as a diagonal brace, and a half-turn staircase forms a K-shaped brace as shown in the picture.(Ahirwal *et al.*, 2008)

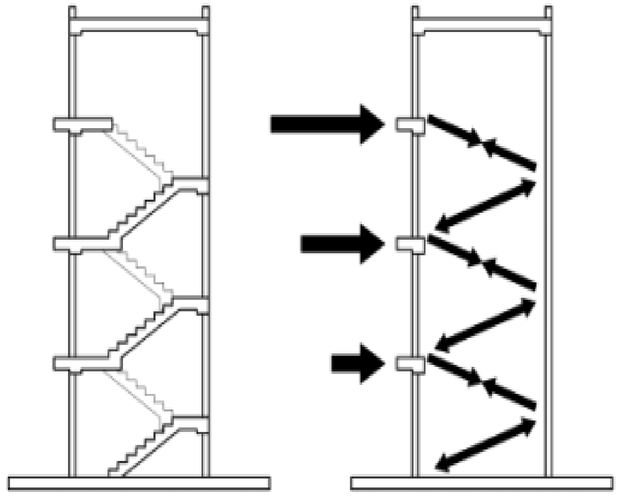


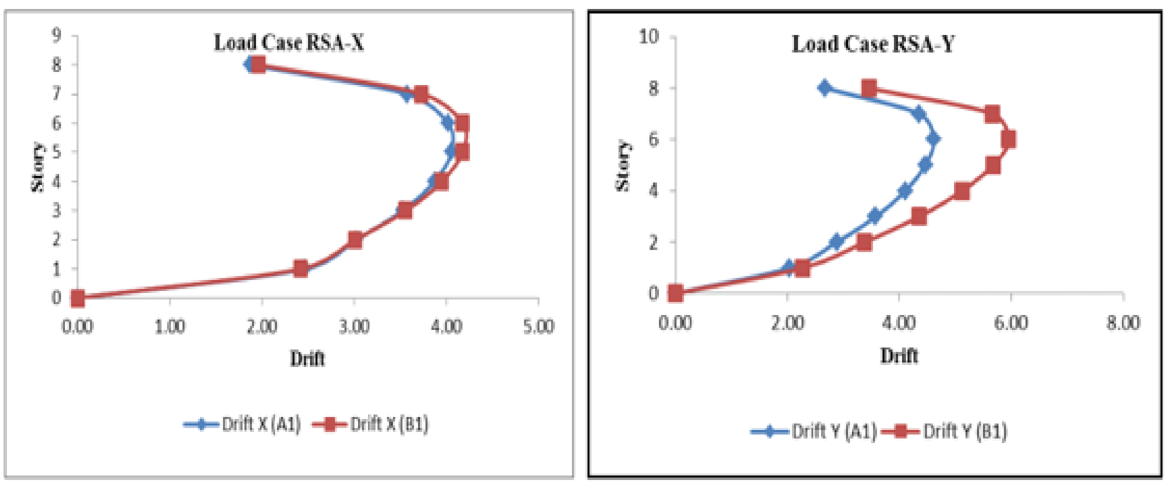
Figure 2.1: K-shaped bracing performance of staircase attached to structure

Because the stiffness of the stair is more than frames at the moment, so it could absorb more forces and a concentration of stiffness will occur in a part of the structure, since these elements are not considered in the structural modeling as usual, so its effects on the structure are remain as not analyzed.(Ahirwal *et al.*, 2008)

(Shyamananda Singh, 2012) presents the effects of staircase on the seismic performance of the reinforced concrete frame buildings of different heights and different plans have been studied Generally, the staircase model is not included in the analysis of reinforced concrete frame buildings. Because of the stiffness of the sloping slab and the short columns around the stairs, the beams and columns are often characterized by high seismic interest. The identification of the most vulnerable components of the structure, the nature of the failure, taking into account the presence of the staircases, and their contribution and commitment to the nonlinear performance of reinforced concrete frame buildings are some of the areas this paper has focused on. For analysis and design, ETABS V.9 has been used. The response spectrum analysis method is used to evaluate the performances of each category of the buildings.

From geometrical perspective, a staircase consists of inclined members that can be taken as beam or slab and by short columns. These elements participate in increasing the Stiffness of the building. Because of this reason the elements that associated with stairways are often characterized by a high seismic concentration during design. The short columns provided nearby the stairways are subjected to high shear force which can lead to brittle premature failure. The inclined beams are subjected to high difference in axial force than main variations are arise in the resistance and deformability of all these members. The identification of the vulnerable elements of the structure, the type of failure with the presence of the staircases and the contribution of the stairs in the non-linear performance of the reinforced concrete frame buildings are some of the ideas that have been taken into account in this study.(Deshmukh and Banarase, 2017)

(Shelotkar, 2016) presents the effect of staircase position on RC frame structures has been carried out by adopting various building models with and without staircase in longitudinal and transverse direction. The Linear Response Spectrum analysis of the models has been carried out as per IS: 1893 (Part 1) - 2002 and IS: 456 – 2000 with the help of ETABS V.2015 software. The Seismic characteristics in terms of Time period, Story Drift and Story Displacement have been compared with the seismic characteristics of models with and without a staircase. Further, the effect of change in location of the staircase on the behavior of the building has also been observed. In addition, the effect of the short column, the variation in the moments of the beams and columns attached to the stair slab, and the failure and deformation in stair models were also observed.



a) Story drift in X with stair (A1) and without stair (B1)

b) Story drift in Y with stair (A1) and without stair (B1)

Figure 2.2: Story drift a building with and without staircase

(Danish *et al.*, 2013) evaluated the effects of staircase on reinforced concrete frame building by implementing various building models (a bare frame without stair, a frame with infill panels and a frame with infill except first stories) with and without staircase and number of stories of the building has been wide-ranging from 4 stories to 10 stories. Analysis of the models has been done by linear Response Spectrum analysis as per IS: 1893 (Part 1) – 2002 and IS: 456 – 2000 with the help of FEM based software. Seismic properties in terms of Mass Participation Factor, Time period, and story drift have been compared with the seismic properties of models without stairs. Further, the effect of changing position of staircase in the building has also observed. the variation in the moments of beams and columns that are joined to the stair slab, failures and deformations in stair models and the comparison of infill panel effects in addition of these, the short column effect has also been studied.

The staircase is the vertical transport way among stories, it is a very important building component. the stairways are extremely damaged in an earthquake, and it failed to achieve the required role for a person to evacuate from the building in case of emergency. frame structure with reinforced concrete plate stairs are taken as an example during finite analysis is used. Evaluation result indicates that the plate staircase has a great impact on the behavior of the structures earthquake resistance. Designing a building without the plate staircase into account would lead to structural weakness in surrounding columns and cause extreme damage under earthquake excitation and affect the safety of the building structure. A staircase arrangement can affect the torsional mode of the structure, whereby the torsional mode can be the first vibration mode. Their investigation shows that shear failure becomes major in the squat plates and columns and precedes traditional ductile failure. (Qiwang, 2010).

The staircases enhance the structural strength and rigidity of a building but it is attracting seismic forces it might fail into inclined beams holding the steps a cause of high axial forces., into its short columns, or into the slabs because of its high shear forces. The fundamental courses of action and arrangement practice of stairwell in gravity load arranged plans are inspected to portray their certified numerical definition and to comprehend their presentation. Some mathematical modal linear and non-linear push-over analyses are presented here. A representative reinforced concrete building maintaining the materials and design requirement of the due time is considered for the evaluation. Specifically, the staircase type is considered: the stair containing simply supported slabs and the one with cantilever staircase constrained in inclined beams. The modal analysis highlights the different modal behavior taking into account the staircase. A non-linear took plasticity model permits carry-out non-linear pushover analysis which allows finding the major failure mechanisms. Some numerical simulations provide some interesting responses and offer some upright features on the problems associated with the geometrical and mechanical modeling of the structural members of the staircase, and to the principle categories of failure caused by flexural, or shear. The figure below shows the push-over analysis result in transversal and longitudinal directions.(Cosenza, Verderame and Zambrano, 2008)

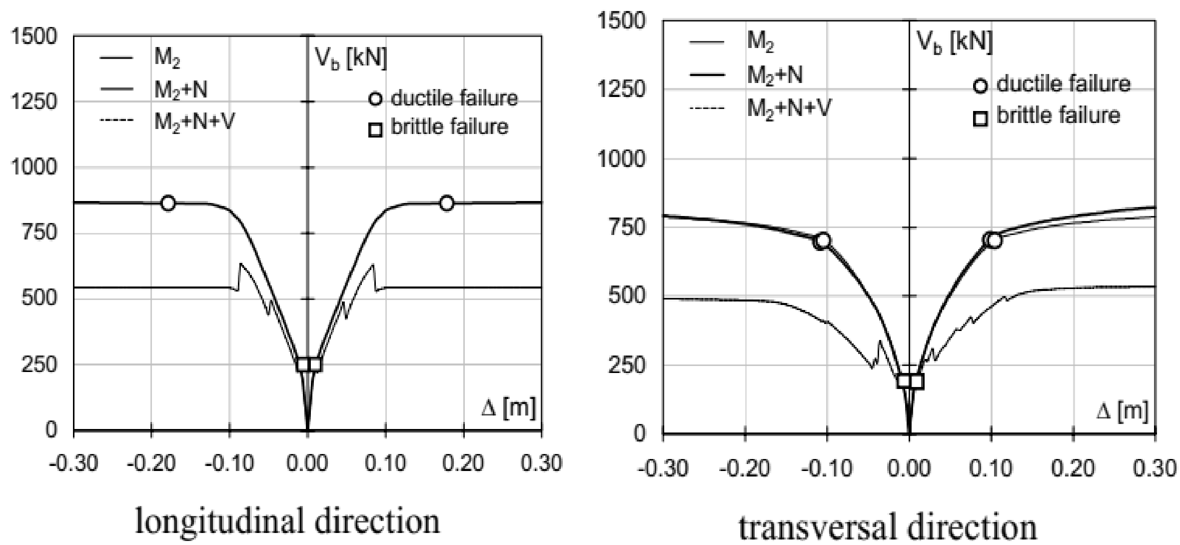


Figure 2.3: Results of the push-over analyses

The theoretical design is constantly used to think about the effect of the staircase on the underlying performance during the past seismic design of buildings, for instance, the short columns nearby staircase should have sufficient stirrups in its full-length, the asymmetrical layout of the staircases possibly make a substantial torsion effect to the entire structure. Dual computer models of a reinforced concrete frame with stairs were made and the seismic response of the models in elastic-phase was evaluated by implementing the base shear method, spectrum analysis using ETABS software. The results give confirmation to the idea that including a staircase into 3D models will affect the seismic responses of frame building significantly. The study proposes that the computer model with stairway and the response spectrum analysis must be used initially in the seismic design of the reinforced concrete frame with stair.(Cao, Bian and Xu, 2014)

Because of the importance of stair performance, which allows residents to exit the building, they play an important role in the building and their seismic performance is so important and should be considered. The paper has analyzed two series of models using ETABS. In this series, an appropriate analysis was carried out on the effects of stairs in 6-story buildings while they are at the corner of the building and near the center of the building. The response of the linear analysis shows that in the concrete structure, it is important to consider the modeling of the structure since it causes additional stiffness and change in the coordinate of the center of stiffness so that its effects are significant while the position of the ladder is far from the center of the rigidity of the structure by not having the stairway. These effects can be estimated in the period, torsional moment, stiffness, displacement, and column force of the structure.(Aghajani-delavar and Varnosfaderani, 2017)

Torsional irregularity leads to amplified unequal displacements at the excesses of the building and may result distress in elements that resists lateral load at the edges. Torsion is twisting moment produced in structures. These effects arise due to diverse reasons, such as inconsistent distribution of the building mass, strength and stiffness etc. In a buildings mass asymmetry is often occur at different floor level. This mass asymmetry could be due to elevated water tank placed at top of building, some heavy weight machine located at any level, etc. consequently, mass center of the building could shift from center of stiffness initiating eccentricity. As eccentricity increases, torsional response in the building also increases.(Ghodke and U.R.Awari, 2016)

2.2. Lateral force resisting systems

Concrete building shall be classified into different structural system according to their behavior under horizontal seismic actions.

2.2.1. Moment-resisting frames

The straight assemblages of beams and columns where there is a rigid connection between beams to the columns are known as moment-resisting frames. Lateral load resistance of MRF is provided by bending resistance of columns and girders. Horizontal actions (story shears) generate shear in columns which bend in double curvature. Lateral stiffness of a rigid-frame bent depends on the relative flexural stiffness of the columns, girders and connection. Moment - resisting frames are economical only for buildings up to about 20 storeys. Rigid frame is ideally suitable for reinforced concrete building because of inherent rigidity of reinforced concrete connection.(Elnashai, 2008)

Frames could be designed using the principle of strong column-weak beam proportions. there are two major types of MRF. The first one is the Ordinary Moment Resisting Frame (OMRF) which is a moment-resisting frame not comply with special detailing requirements of building for a ductile behavior. The second is Special Moment Resisting Frame (SMRF) which is a moment-resisting frame specially detailed to offer ductile behavior.(Titiksh and M K, 2015)

2.2.2. Braced frames

Braced frames are lateral force- resisting systems which consist of beams, columns, diagonal braces and joints. Many brace configurations may be efficiently employed to withstand earthquake loads. Braced frames are often grouped into two categories, i.e. concentrically braced frames and eccentrically braced frames depending on the layout of the diagonals employed.(Elnashai, 2008)

2.2.3. Wall systems

Structural system in which both vertical and lateral loads are mainly resisted by vertical structural walls, either coupled or uncoupled wall system.(ES EN, 2015)

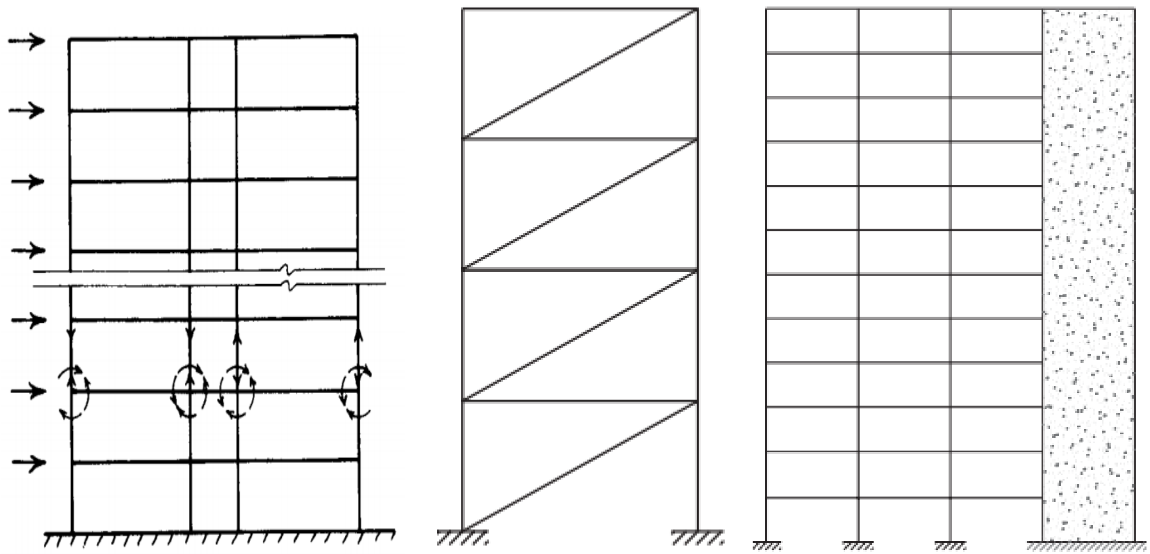
2.2.4. Dual frames

Structural system in which support for the vertical loads is mainly provided by a spatial frame and resistance to lateral loads is contributed to in part by the frame system and in part by structural walls, coupled or uncoupled.(ES EN, 2015)

2.2.5. Tube systems

Tube systems are structural systems in which lateral stiffness and strength are provided by MRFs, braced frames, shear wall or hybrid systems that form either a single tube around the perimeter of the structure, or nested tubes around the perimeter and core of the structure. Tube systems are frequently used for high-rise structures; they include the following:(Elnashai, 2008)

- Framed tubes;
- Trussed tubes;
- Tube-in-tube;
- Bundled tubes.



(a) Moment resisting frames (b) Braced frame (c) Dual frame

Figure 2.4: Structural systems

Table 2.1: Efficiency of lateral resisting systems for seismic applications

Lateral resisting system	Stiffness	Strength	Ductility	Ductility	
				Max. number of storeys	**Seismic application**
Moment - resisting frame	L	H	H	15-20	✓✓
Braced frame	H	H	L-M	20-30	✓
Structural wall	H	H	L-M	25-30	✓
Hybrid (or dual) frame	H	H	M-H	30-40	✓✓
Outrigger - braced frame	H	H	L-M	50-60	✓
Framed tube system	H	H	M-H	60-70	✓✓
Tube - in - tube system	H	H	M-H	70-80	✓✓
Trussed tube system	H	H	M-H	80-100	✓✓
Bundled tube system	H	H	M-H	120-150	✓✓

Key: H = high; M = moderate; L = low; ✓ = suitable; ✓✓ = very suitable

Source:(Elnashai, 2008)

2.3. Types of earthquake analysis Methods

Earthquake or seismic analysis is a part of structural analysis and design which comprises the evaluation of the response of a structure subjected to earthquake action. This analysis is important in carrying out the building design, structural assessment, and retrofitting of the structures in the regions prone to earthquakes excitation. Numerous seismic data are required to perform analysis of structures subjected to seismic force. These data are obtained either in deterministic form or in probabilistic form. Data obtained in the deterministic form are used for the design of various structures. Data obtained in the probabilistic form are used mostly for the study of structural elements subjected to random vibration, seismic risk or hazard analysis, and damage assessment of structures under certain earthquake ground motion. Major seismic input involves ground acceleration, velocity, displacement data, peak ground parameters, the magnitude of the earthquake, duration, etc. For the evaluation of the seismic response, the linear state of stress is usually used, in complicated cases or due to the greater importance of the structure, it is recommended to use a non-linear method.

2.3.1. Lateral force method

Lateral force method is linear (material and behavior) and a static evaluation using horizontal forces as a seismic load. By this method a high frequency cannot have the decisive influence. The base shear force able to be assigned for each direction. The distribution of the horizontal forces increases linearly or reacts to the eigenvalues. Every story has to be rigid in its level.(Čada and Máca, 2017)

Equivalent static lateral force method gives higher response values of moments forces and which leads design of the building uneconomical so that consideration of response spectrum method is also required. (Ramakrishna and Riyaz, 2017)

2.3.2. Modal response spectrum analysis

In order to carry out the seismic analysis and design of a building to be constructed at a particular seismic hazard zones, the actual time history record is required. However, it is difficult to have such recorded time history data at every location. Further, the structural seismic analysis cannot be performed simply depending on the peak ground acceleration value as the response of the structure depend upon the ground motion frequency and its own dynamic properties. Response spectrum is the most important and popular method in the seismic analysis of structures to overcome the above-mentioned analysis difficulties. Response spectrum method is computationally advantageous in seismic analysis for estimation displacements and forces in structural systems.(Spectra, 2002)

Modal response spectrum analysis is a dynamic method with the same geometrical rules as by the lateral force method. This method gave us better results. This is a good choice for more complicated structures. Members of the structure are with this analysis not so much oversized. It is widely used in the practice.(Čada and Máca, 2017)

Response spectrum analysis depends on the following major seismic parameters;

- Mechanism of energy releasing and behavior factor of the structure.
- Peak ground acceleration, *ag*
- Soil condition, S
- Richter magnitude
- Damping in the system, η
- Time period of the system, T

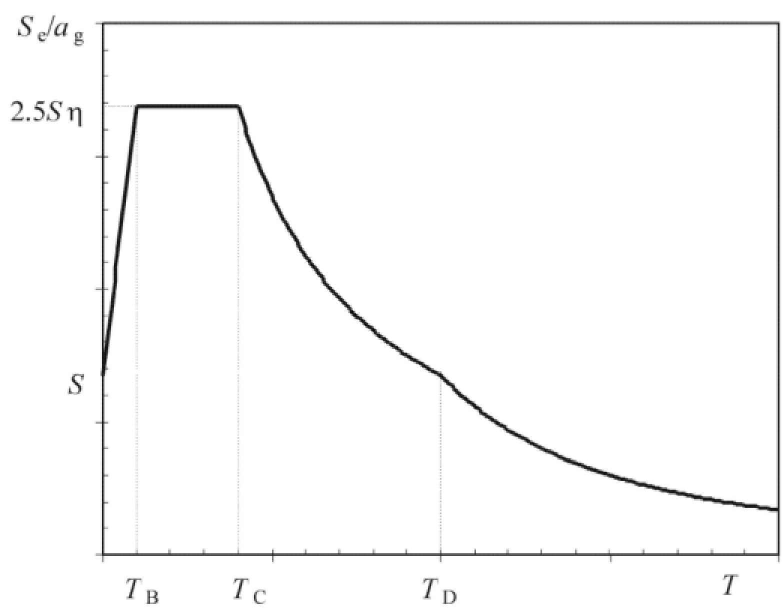


Figure 2.5: Shape of elastic response spectrum

2.3.3. Non-linear time-history (dynamic) analysis

Time-history analysis is non-linear methods of seismic evaluation that based on direct mathematical integration of the differential equation of motion. Motion or vibration of the base is expressed and represented using the accelerogram. The time-history analysis is preferable for known past earthquakes analysis.(Čada and Máca, 2017)

2.3.4. Non-linear static (pushover) analysis

The pushover analysis is usually preferred for analysis and design of new buildings or reconstructions. Pushover analysis is a nonlinear static analysis method in which the building structure is subjected to gravity loads and therefore will experience a monotonic displacement manipulated lateral load arrangement which increased to reach the ultimate condition. In pushover analysis, lateral load arrangement should be selected wisely and as per the provision of the building codes.(Ramin Taghinezhad, Arash Taghinezhad, Vahid Mahdavifar, 2018)

A pushover-based analysis represents a rational practice-oriented method for the seismic analysis of structures. Compared with traditional elastic analyses, pushover analysis provides a wealth of additional important information about the anticipated structural response, as well as insight into the structural aspects that controls performance during severe earthquakes.(Kabtamu Getachew, et al., 2020)

2.4. Geometrical classification of staircases

Staircases can be classified on different bases such as support conditions (simply support, fixed support and cantilever) and geometry (strait flight and curved/helical staircase). For this research purpose I only consider the geometrical classification to investigate their effect on seismic response of the building structures. (http//: slideserve.com)

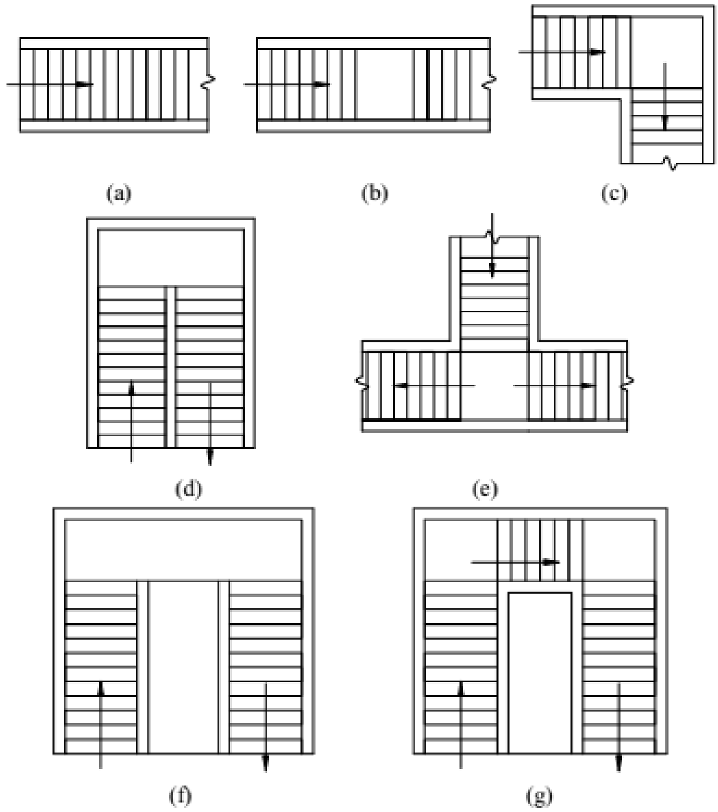


Figure 2.6: Strait flight staircases

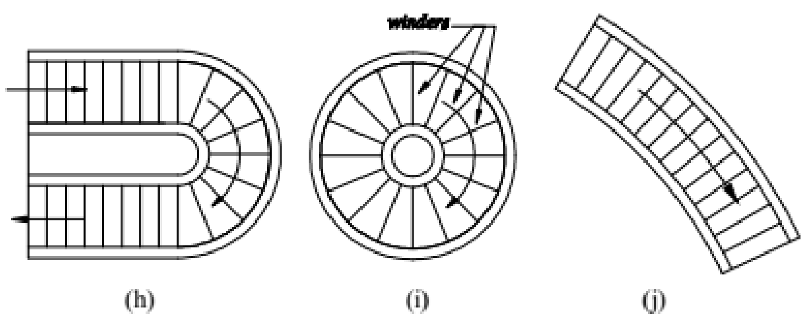


Figure 2.7: Curved/Helical staircases

2.5. Earthquake response of structures

2.5.1. Displacement/Drift

Drift can be defined in the form of total drift which is the total horizontal displacement at the top of the building structures. The relative lateral displacement that takes place between two consecutive building floor levels is known as inter-story drift. The drift index is a simple evaluation of the lateral stiffness or rigidity of the building and is used almost independently to limit possible damage to nonstructural components of the building. Inter story drift ratio (IDR), can be defined as the relative lateral translational displacement between two successive floors divided by the height of the story. The equation defined below express the drift index.(Patil Jaya and Alandkar, 2016)

Drift Index = displacement/height

Total Drift Index = Total drift/Building height = Δ/H

Inter story drift index = Inter story drift/story height = δ/h.

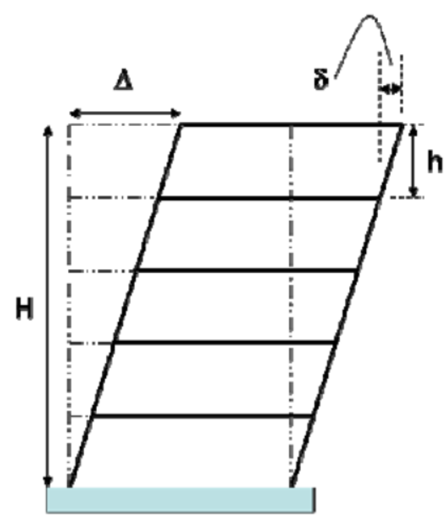


Figure 2.8: Drift measurement (Patil et al.,2016)

Story drift is defined as the displacement of one-story level relative to the other story level above or below. The story drifts have been usually used to calculate expected damage to the structure during earthquake excitation.

2.5.2. Base shear

Base shear is an evaluation of the maximum expected horizontal force that will occur because of seismic movement of the ground at the base of a structure. Its magnitude is affected by the condition and properties of the site. Base shear is calculated by summing the horizontal force at each floor level about the base of the building. (Kolekar and Pawar, 2017)

2.5.3. Base overturning moment

The moment cumulated at the base of building structure due to story shear at each floor level different loading conditions on the structure is known as base overturning moment. Overturning moment occur at the base of building in X direction is caused by the lateral force in Y direction and vice versa. (Kolekar and Pawar, 2017)

2.6. Summary

The studies conducted so far focused on the effect of including or excluding the staircase as the main structural element in the modeling of the structure for 3D analysis. Moment resisting frame considered as type structural system with varies story numbers up to 10 stories. The overall result of past studies shows that the vulnerability of staircase element, when subjected to the earthquake as it imparts additional stiffness to the building, for these reasons the elements that constitute the staircases are often characterized by high seismic demand. The location of the staircase has a significant impact on the seismic response of the building structure. Because it provides additional considerable lateral stiffness. It can also affect the entire distribution of lateral force to the frame of the building. Also, Due to stiffness concentration around the stair, columns located near the staircase has higher seismic demand and subjected to maximum shear.

2.7. Research gaps

A lot of researches have been done on the overall effect of a staircase on seismic response of building and consequent damage related to excluding stair from modeling it as main structural part. But the clear demarcation on type of staircase and in what orientation staircase provided, the effect is significant isn't addressed. The studies only focused on a single type of staircase (Doglegged staircase). So new research is required to identify which type of staircase and on which orientation the effect is severe in addition to its location.

Accordingly, this research paper is intended to integrate the effect of plan irregularity with staircase location, type, and its orientation on the seismic response of the medium-rise building. It is also necessary to make the study area at one of the higher seismic regions in Ethiopia so that, the study will be more helpful as good input for Architects and engineers.

Each type of staircase considered in this study is different in the way they supported and brace adjacent columns. In previous studies, the effect of 180^o turn staircase with one landing (doglegged) is only studied. This type of staircase provides a 'K' type of bracing on supporting columns. To properly understand the technical difference between stairs, the force interaction of respective staircases is shown in the figure below.

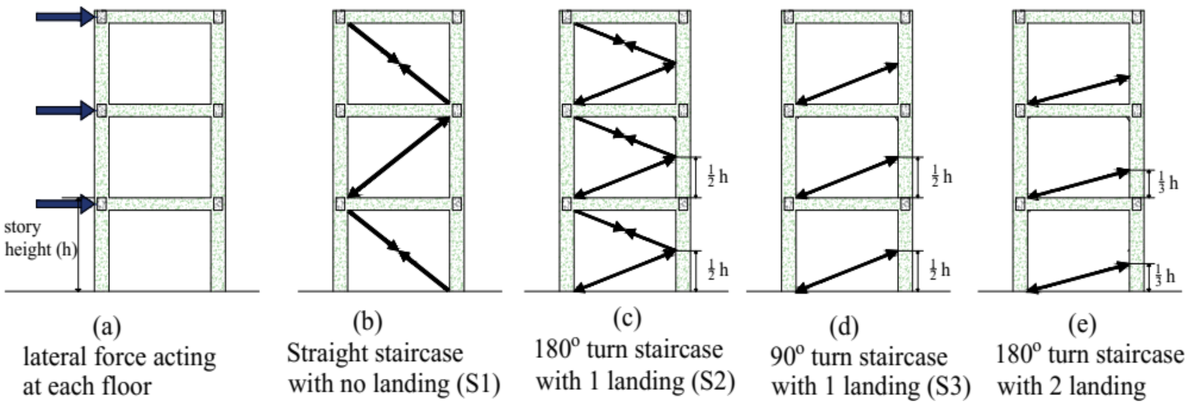


Figure 2.9: possible force interaction of different staircase type to lateral load

Figure 2.8 a) shows the lateral force applied at each floor level where the staircase is to be provided. The straight flight staircase shown in figure (b) will not have intermediate bracing on the column. But it acts as diagonal bracing between the story and inclined shear wall in either direction, which provides a significant contribution in lateral load resistance. Figure (c) shows doglegged staircase which acts as 'K' bracing according to a literature review of previous studies. Figure (d) shows the possible force interaction of 90^o turn staircase with one landing (L-shape). This stair provides half bracing to the story at its mid-height in both orthogonal directions. Unlike other types of stairs, L-shape stair responds against seismic action in X and Y direction hence preferable for regular building with the staircase at the center. Figure (e) shows 180^o turn staircase with two landings (U-shape) which brace supporting columns at one-third of its height in both orthogonal directions.

Generally, new research that covers another common type of staircases mentioned above was required to study their effects on earthquake response of buildings. Because the investigation enhances proper utilization of the staircase from a structural perspective in high seismic regions of Ethiopia. Also, effects of staircase location and orientation in orthogonal directions in terms of different seismic parameters including story stiffness and eccentricity required to be investigated.

CHAPTER THREE

RESEARCH METHODOLOGY

This section aims to present the procedures, considerations, and methodology used for the investigation of the effect of a staircase on earthquake response of medium rise MRF building using RSA. All the necessary procedures and provisions recommended by the new version of the Ethiopian Standard (ES EN, 2015) are followed with justifications.

3.1. Study Area

Adama town is considered as the study area for this research since it is located in a great rift valley which is characterized by high seismic hazard. It is located at 08°32′29″N 39°16′08″E/ 8.54139°N 39.26889°E Latitude and Longitude respectively at an elevation of 1,712 meters (5,617 ft.), 84 Km on high way, Southeast of Addis Ababa along the main road to Harar. The study area is selected based on ES EN 1998-1: 2015 for seismic hazard zonation of Ethiopia.

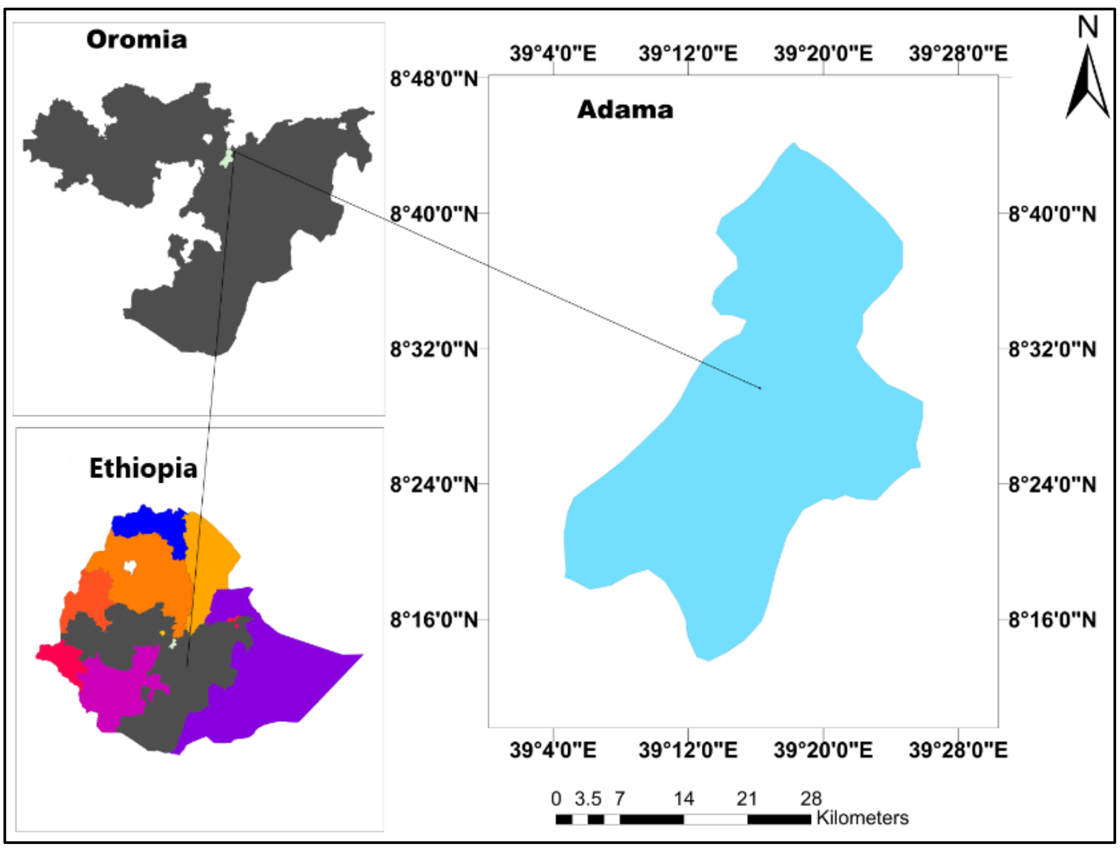


Figure 3.1: Geographical Map of Adama town, Ethiopia

3.2. Research Design

Based on how the research is done, the type of this research is exploratory research as it intended to explore the effect of a staircase on earthquake performance of Moment Resisting Frame (MRF). The effect will be presented in terms of displacement, story drift, base shear, base overturning moment, story stiffens, and eccentricity. Since the research is associated with earthquake performance of stairs, other sources of lateral loads will not be considered.

Response spectrum analysis (RSA) is adapted as an earthquake analysis method for the investigation. Because RSA uses a dynamic analysis approach to yields the most reasonable result. It is also widely used since it is a linear seismic analysis method and a previous record of earthquake events is not required like for time history analysis (THA). All the analysis is executed by structural analysis software, ETABS, V.18 as per the newly revised Ethiopian standard based on European norm (ES EN, 2015)

3.3. Study Variables

3.3.1. Dependent Variables

- Displacement
- Story drift
- Base shear
- Base overturning moment
- Story stiffness
- Eccentricity

3.3.2. Independent Variables

- Number and height of the building story
- Peak ground acceleration coefficient
- Magnitude of dead and live load
- Cross-sectional dimensions of structural members.
- Concrete grade
- Location of staircase
- Structural behavior factors (ductility and damping coefficients).

3.4. Population and Sampling Method (Descriptive Research)

3.4.1. Sample Size

The sampling size of this research has a total of 18 modeling. 4 types of a staircase are selected based on the number of landing and degree of turning. 2 types of building plan (regular and irregular) is considered, in such a way that each plan type is modeled with and without a staircase. To evaluate the effect of location, the stairs are provided at two locations (center and corner of the building) independently with different modeling. accordingly, all the samples are classified into 5 groups so that the result of the research is easily presented.

3.4.2. Sampling Procedure

Since the research has multiple dependent variables, the sampling procedure may not easily understand unless explained by a relevant diagram. As explained in the preceding section, the two buildings (regular and irregular plan) will be modeled with staircase and without staircase to evaluate the overall effect of a staircase on the seismic response of RC building. for each of the buildings modeled with a staircase, there is location and staircase type change so that all the intended parameters are covered in the research. All the samples are grouped into 5 groups (G1-G5) base on the building plan regularity modeled with or without a staircase and the location where the staircase is provided. The detailed sampling procedure is explained in the form of a flow chart as follows.

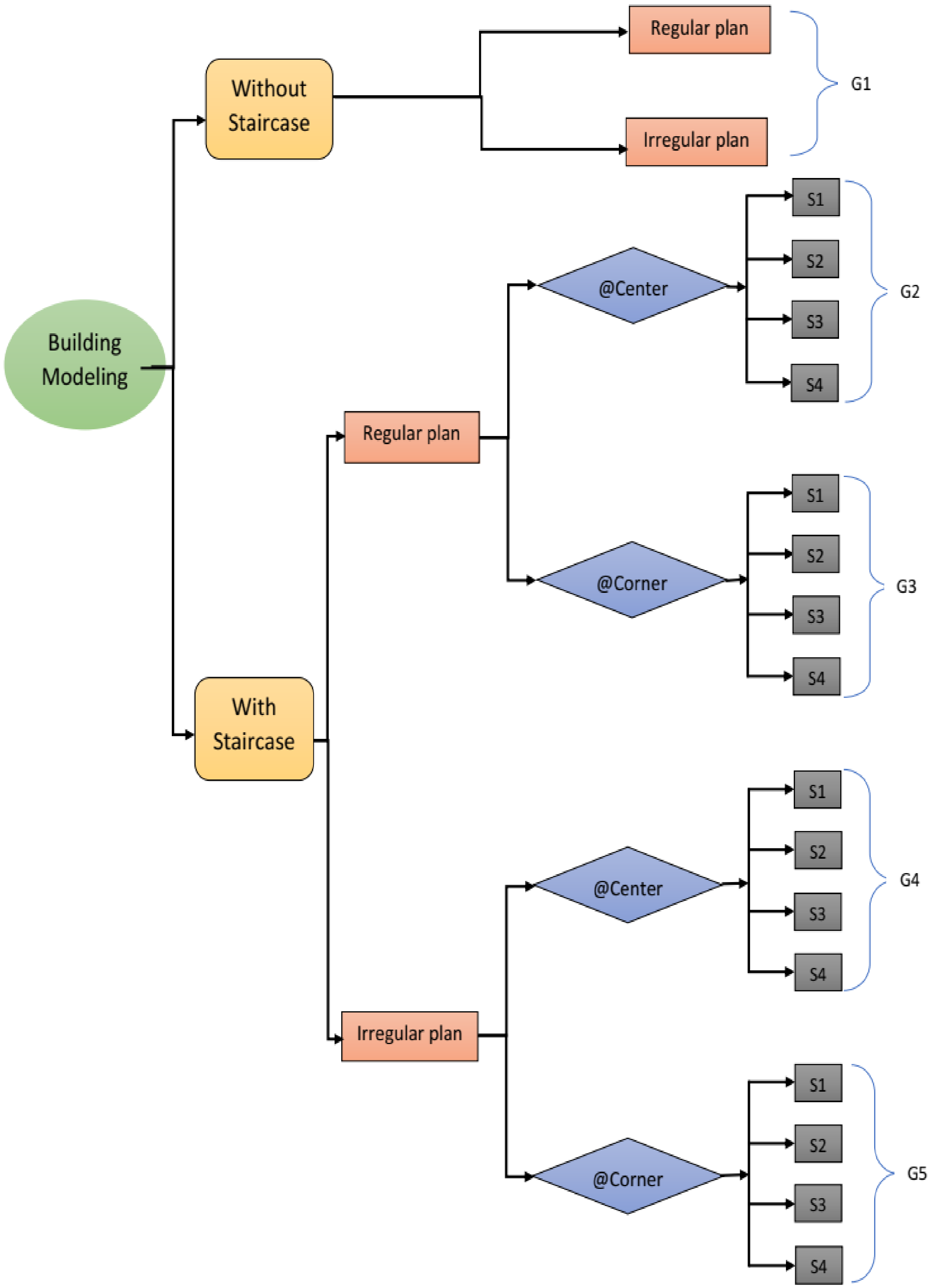


Figure 3.2: Sampling procedure flow chart

3.5. Source of Data

The data used for this research is obtained from guiding codes, mainly from code and different literature. The necessary data required for the investigation, is present the way the buildings to be modeled with respective material and section of structural members.

3.5.1. Summary of seismic and structural data

Table 3.1: Modeling parameters and respective value

Parameter	Type/Value	Remark
Structure type	Reinforced concrete	MRF
Regularity of the structure	Both regular and irregular plan	
Number of stories	8 stories	
Bottom story height	3m	Constant story height
Top stories height	3m	
Area of structure	992.25m^2 (regular plan) & 668.25m^2 (irregular plan)	
Bay Width in both direction	4.5m	Constant bay width
Material properties		
Grade reinforce steel	S-300	fyk=300Mpa
Concrete Strength	C20/25	fck=20MPa
Modulus of elasticity of concrete	30Gpa	
Modulus of elasticity of steel	200Gpa	
Density of reinforced concrete	25 kN/m^3	
Member properties		
Beam type	300mm X 400mm	For all story beams
Column type	500mm X 500mm	Constant throughout
Thickness of slab	140mm	ES EN 1992, 1-1: 2015, sec 7.4.2
Thickness of staircase slab	140mm	
Loading (According to ES EN 1991-1-1: 2015)		
Live load	5 KN/m^2 for typical floor	Sec:4.2.5 Category D
	1 KN/m^2 for roof	
Seismic Factors (According to ES EN 1998-1: 2015)		
Seismic zone	IV	Adama (study Area)
Peak Ground Acceleration	0.15	Annex D1
Importance factor, *r*	1.2	Sec:4.2.5
Spectrum type	I	Sec:3.2.2.2
Ground Type	C	Sec:3.2.2, Table 3.1
Behavioral factor, *q*	Regular = 3.9, and Irregular = 3.45	Sec:5.2.2.2
Ductility class	Medium ductility class (MDC)	Sec:5.2.2.2
Lower bound factor/beta (β)	0.2	Sec:3.2.2.5
Correction factor/lambda (λ)	0.85	Sec:4.3.3.2.2

3.5.2. Building layout

Two 8-story buildings with a regular and irregular plan are considered for the analysis. The regular plan building is square shape so that it helps to evaluate the effect of staircase orientation at the same location. The irregular plan helps to integrate the effect of staircase parameters with plan irregularity on the seismic response of the building. The section of all structural members including staircase slab thickness is given in the modeling section of this research. The functional class of building is a mixed-use building which categorized as Category 'D' as per ES EN 1991-1-1:2015

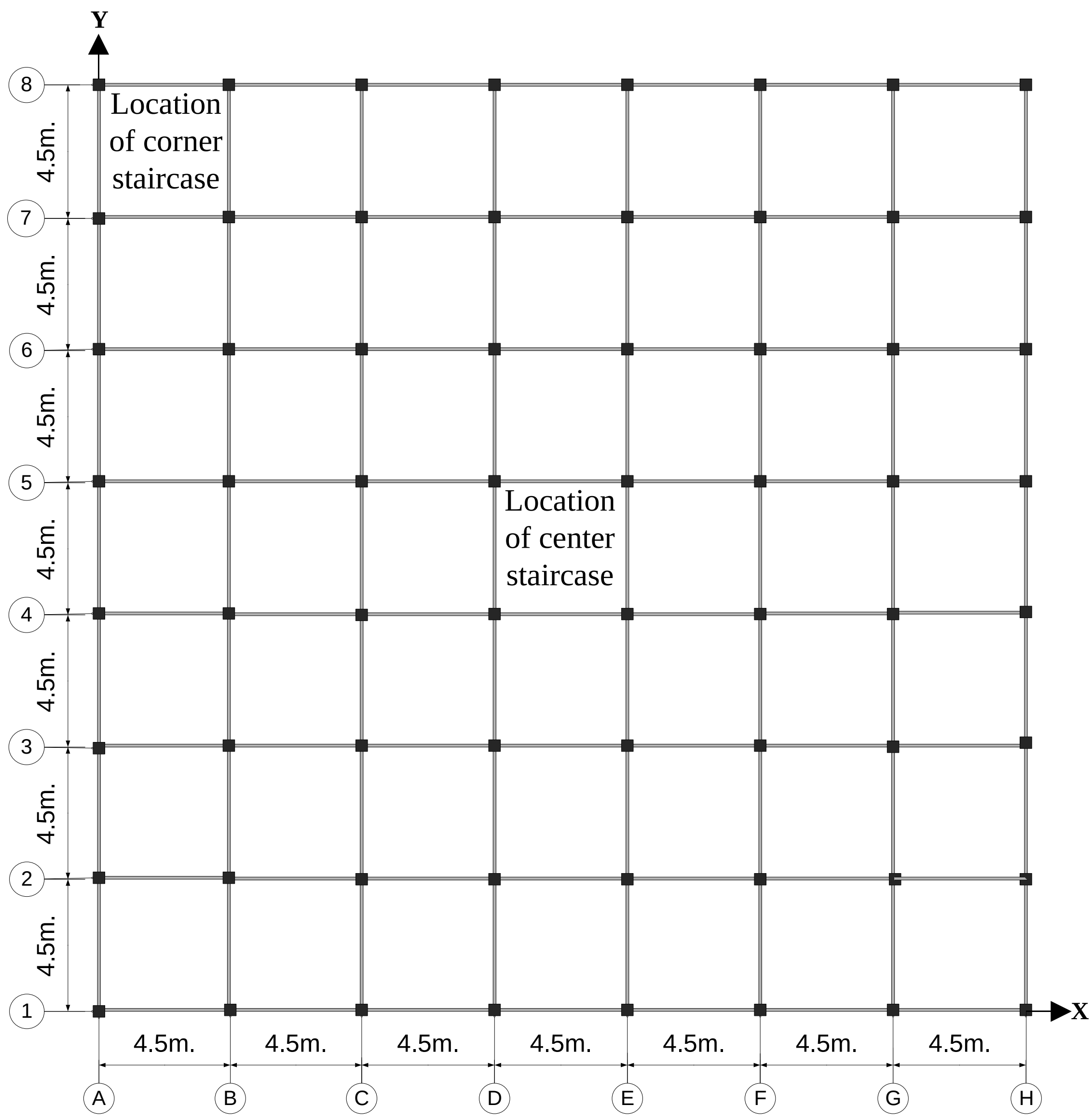


Figure 3.3: Regular plan(square) building

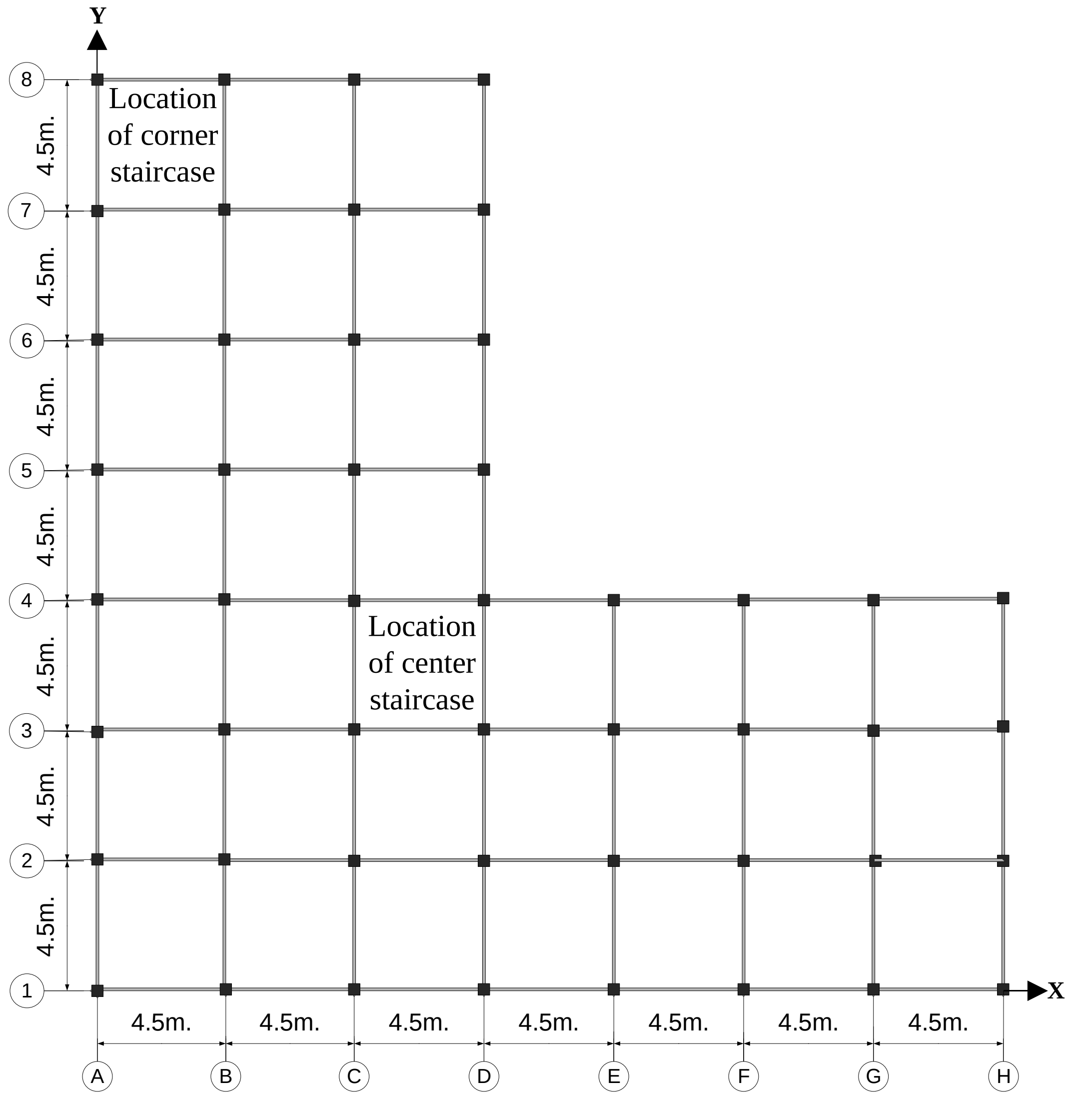


Figure 3.4: Irregular plan(L-shaped) building

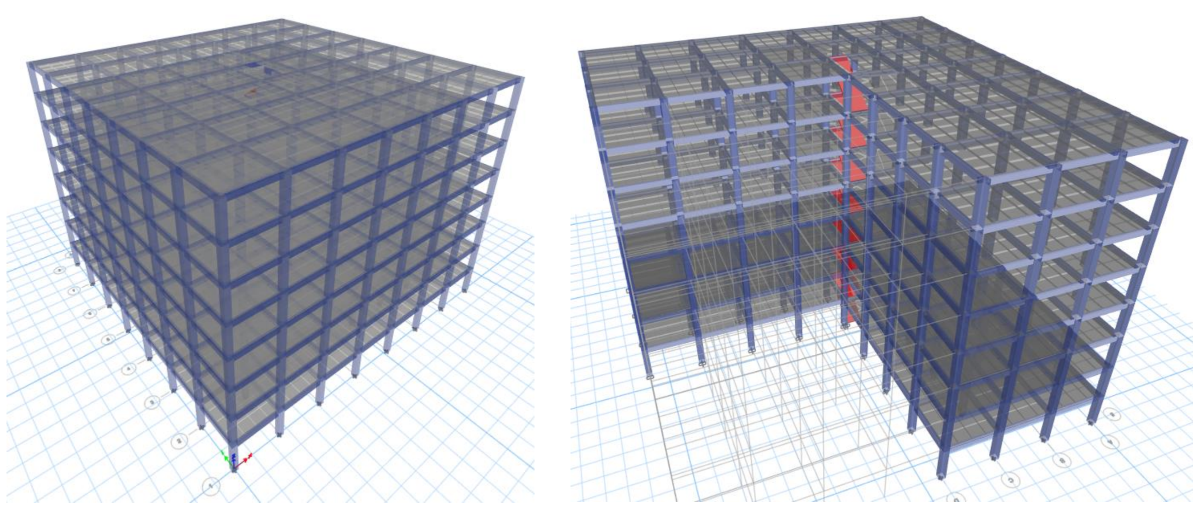
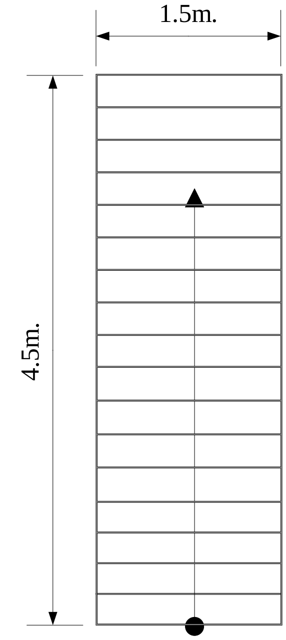


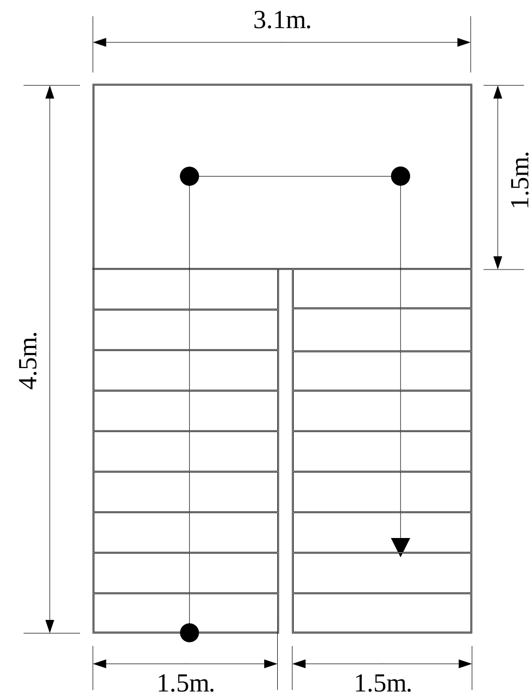
Figure 3.5: 3D view of regular and irregular plan building

3.5.3. Staircase layout

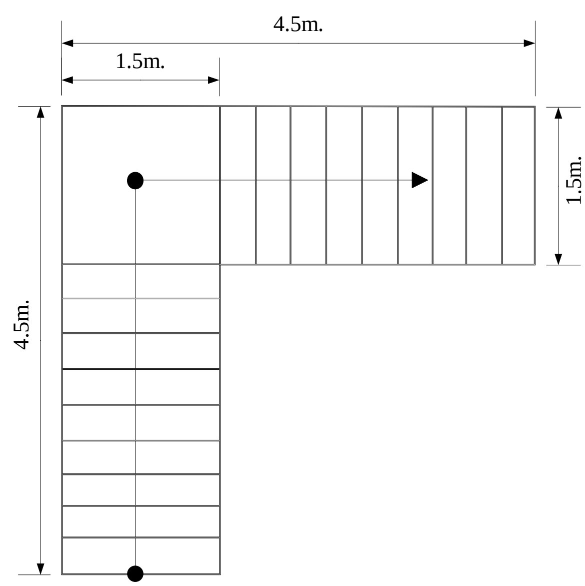
Four mostly used straight flight type of staircase is selected for the research purpose. For simplicity, these staircases are named S1, S2, S3, and S4 as given in the figure below.



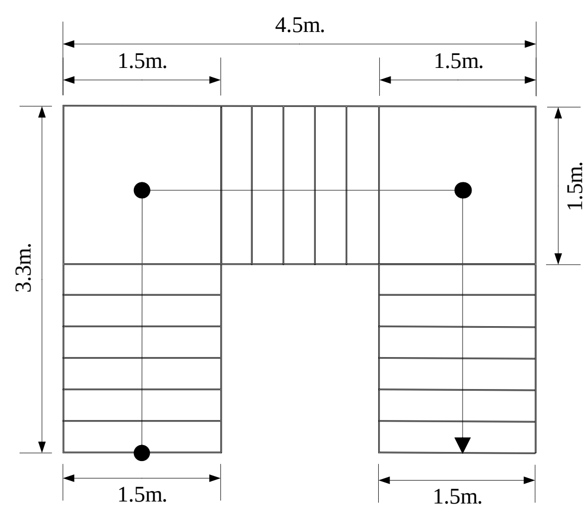
a) Straight stair with no landing, S1



b) 180° turning stair with 1 landing (Doglegged), S2



c) 90° turning stair with 1 landing (L-Shaped), S3



d) 180° turning stair with 2 landing (U-Shaped), S4

Figure 3.6: Selected staircase type for research

3.6. Data Collection Procedure

The method engaged in this research involves quantitative data. The necessary data for the research is collected through a continuous literature review related to the title and from codes. The necessary data and provisions available on the new version of the Ethiopian standard base on European Norm (ES EN, 2015) will be used.

3.7. Data Analysis and Presentation

3.7.1. Data Analysis

Analysis of the data of this thesis is executed by structural analysis software package, ETABS V.18 based on the new version of the Ethiopian standard (ES EN, 2015). Response spectrum analysis (RSA) is adopted as a seismic analysis method. All the seismic parameters are properly defined on the software for data analysis. The seismic analysis is performed by response spectrum load case whereas the modal combination used is Complete Quadratic Combination (CQC) because it is a modal combination technique that accounts for modal damping and the most realist approach.

Since mass source in the seismic analysis is accounted from self-weight of the building and externally applied loads, the possible weight of floor finishing and partition load are considered and assigned to be added on dead load. Live load is also assigned since it should be added to mass source in seismic analysis with the factor recommended by the code depending on the functional class and importance factor of the building.

3.7.2. Data Presentation

Finally, the result of this thesis is presented using tables, graphs, and charts. Presentation of the investigation compered along with the control group in terms of the following seismic response parameters so that, conclusion and recommendation will be drawn.

- Lateral Displacement
- Story drift
- Base shear
- Base overturning moment.
- Story stiffness and eccentricity.

3.8. Detailed seismic data modeling methods

Under this section detailed source of seismic data used in modeling the structure is explained with their respective sources. Accordingly, the source of these modeling data is obtained from ES EN, 2015 of different sections. Another reference is also used on the area that needs detailed investigation such as soil or ground type.

3.8.1. Material

Concrete

- Grade C20/25 for supper-structural part
- Factor of safety =1.5……………..… ES EN 1992, 1-1: 2015, Table 2.1
- $f_{ck} = 20$ MPa …..…………...……...ES EN 1992, 1-1: 2015, Table 3.1
- $f_{cd} = \frac{0.85 f_{ck}}{1.5} = 11.333$ MPa
- $E_{cm} = 30$ GPa ……..………….…..... ES EN 1992, 1-1: 2015, Table 3.1

Reinforcing steel

- S-300
- Factor of safety =1.15….…………... ES EN 1992, 1-1: 2015, Table 2.1
- $f_{yk} = 300$ MPa
- $f_{yd} = \frac{0.85 f_{yk}}{1.15} = 260.87$ MPa
- $E_S = 200$ GPa…….………….…... ... ES EN 1992, 1-1: 2015, sec: 3.2.7(4)

3.8.2. Preliminary member selection

Cross-sectional area of primary members and staircase are defined according to deflection and ductility requirement for medium ductility class (DCM) provided by code.in ES EN 1992, 1-1: 2015, sec 7.4.2

3.8.2.1. Deflection requirement

Minimum depth of flexural members is calculated using the following formula as provided by the code.

$$\frac{l}{d} = K\left[11 + 1.5\sqrt{f_{ck}}\frac{\rho_o}{\rho} + 3.2\sqrt{f_{ck}}\left(\frac{\rho_o}{\rho} - 1\right)^{3/2}\right] \text{ if } \rho \leq \rho_o \qquad (3.1)$$

$$\frac{l}{d} = K\left[11 + 1.5\sqrt{f_{ck}}\frac{\rho_o}{\rho-\rho'} + \frac{1}{12}\sqrt{f_{ck}}\sqrt{\frac{\rho'}{\rho_o}}\right] \text{ if } \rho > \rho_o \quad (3.2)$$

Where:

- l/d is the limit span/depth
- K is the factor to taken in to account the different structural system
- ρ_0 is the reference reinforcement ratio $= 10^{-3}\sqrt{f_{ck}}$
- ρ' is the required tension reinforcement ratio at mid span to resist moment due to the design loads (at support for cantilever)
- f_{ck} is in MPa units

Initially $\rho = \rho_0$ and $f_{ck} = 20$ MPa

Then using equation above, $\frac{l}{d} = 17.71K$ and correction factors $f_{yk} < 500$ MPa is:

$$\frac{500}{f_{yk}} = \frac{500}{300} = \frac{5}{3}$$

$\frac{l}{d} = 17.71K\left(\frac{5}{3}\right) = 29.517K$ by rearranging for d

$$d = \frac{l}{29.517K} =$$

$K = 1$ for simply supported

$K = 1.3$ for end span

$K = 1.5$ for interior span

$K = 0.4$ for cantilever

Table 3.2: Depth calculation for slab and staircase

Slab No	Le (m)	Ly (m)	Span ratio	Slab type	Slab type based on location	K	Effective depth, d (mm)
Center Panels	4.5	4.5	1.0	Two-Way Slab	Interior	1.3	112.27
Edge and Corner Panels	4.5	4.5	1.0	Two-Way Slab	End Span	1.5	97.30

Considering ϕ12mm reinforcement diameter and 15mm concrete cover the depth of slab is:

d_{max} =112.27mm

$D_{max} = d_{max} + Cc + \frac{\emptyset}{2}$ =133.27mm

D_{used} =140mm

Minimum depth from flexural requirement for beam calculated in the same way and taken as 400mm with 300mm width.

3.8.2.2. Medium ductility class requirement

Material and geometric constraints are taken into account during the selection of dimension of frame elements in addition to behavior factors considered during the definition of response spectrum function to meet medium ductility class requirement set by the code. Medium ductility class requirements associated with reinforcement detailing mentioned in the code are not included in this research. Because the objective is to perform seismic analysis and generating seismic response but not to design the building structural elements.

Material requirement for DCM

The minimum concrete grade for medium ductility class (DCM) shall not be less than C-16/20. Accordingly, the concrete grade for this research is taken as C-20/25 and ribbed reinforcing steel is defined to satisfy material requirements.

Geometric constraint of DCM

The beam and column layout of the building selected for this research has no eccentricity to keep maximum distance between beam and column centroidal axis less than one-fourth of the largest cross-sectional dimension of the column.*bw*. width of provided beam satisfied the following expression given by code.

$$b_w \leq \min\{b_c + h_w; 2b_c\} \quad (3.3)$$

where: b_w is depth of beam, 300mm

b_c is largest correctional dimension of column, 500mm

The dimension of the primary seismic column shall not be less than one tenth of the larger distance between the point of contraflexure and the end of the column. Since the center-to-center length of all story columns is 3m, the provided column conservatively satisfies the minimum dimension requirement for the medium ductility class.

3.8.3. Load calculation

3.8.3.1. Live load

The functional purpose of the buildings considered in this investigation is for mixed-use which is taken as category D as ES EN 1991, 1-1: 2015, Table 6.
for Category 'D' Live load is = 5 kN/m^2………. ES EN 1991, 1-1: 2015, Table 6.1

3.8.3.2. Dead load calculation

Depending on materials used for floor finishing and the possible existence of partition loading dead load on the building is calculated separately for the typical floor, flat roof, and staircase. The floor finish used for dead load calculation is terrazzo which is poured, cured, ground and polished. Typically used as a finish for floors, stairs or walls. Terrazzo can be poured in place or pre-cast.(Karam and Tabbara, 2009)

Table 3.3: Dead load calculation for typical floor

Material Used	**Thickness (mm)**	**unit weight (kN/m^3)**	**Uniform Load (kN/m^2)**
RC Slab	140	25	3.5
Terrazzo Floor Tile	20	20	0.4
Cement Screed	30	23	0.69
Ceiling Plastering	20	23	0.46
Partition Wall Load			1
Total dead load			**2.55**

Table 3.4: Dead load calculation for flat roof

Material Used	**Thickness (mm)**	**unit weight (kN/m^3)**	**Uniform Load (kN/m^2)**
RC Slab	140	25	3.5
Rubber Roof Covering	1.5	17	0.0255
Cement Screed	30	23	0.69
Ceiling Plastering	20	23	0.46
Partition Wall Load			1
Total dead load			**2.18**

Since staircase is the main concern in this investigation the possible dead load on flight and landing portion is considered in load assignment according to the following calculation.

Table 3.5: Dead load calculation for staircase flight portion

Material Used	**Thickness (mm)**	**unit weight (kN/m^3)**	**Uniform Load (kN/m^2)**
RC slab	140	25	3.5
Terrazzo finishing	20	20	0.4
Cement screed	30	23	0.69
Ceiling plastering	20	23	0.46
RC tread and riser	80	25	2
Total dead load			**3.55**

Table 3.6: Dead load calculation for staircase landing portion

Material Used	**Thickness (mm)**	**unit weight (kN/m^3)**	**Uniform Load (kN/m^2)**
RC slab	140	25	3.5
Terrazzo finishing	20	20	0.4
Cement screed	30	23	0.69
Ceiling plastering	20	23	0.46
Total dead load			**1.55**

3.8.4. Response spectrum function

The function of the response spectrum is defined on ETABS V.18 software using the necessary data obtained from code for seismic analysis. These necessary data are presented below along with justification for consideration.

3.8.4.1. Seismic zone of study area

For earthquake analysis, the country has been subdivided into different seismic zones depending on the local hazard. The hazard map is preliminary and is processed from an instrumentally recorded earthquake catalog. The seismic hazard map is divided into 5 zones, where the ratio of the design bedrock acceleration to the acceleration of gravity for the respective zone is indicated in table D1 of ES EN 1998-1: 2015.

Table 3.7: Bedrock acceleration ratio, a_o

Zone	5	4	3	2	1	0
$a_o = \frac{a_g}{g}$	0.20	0.15	0.10	0.07	0.04	0

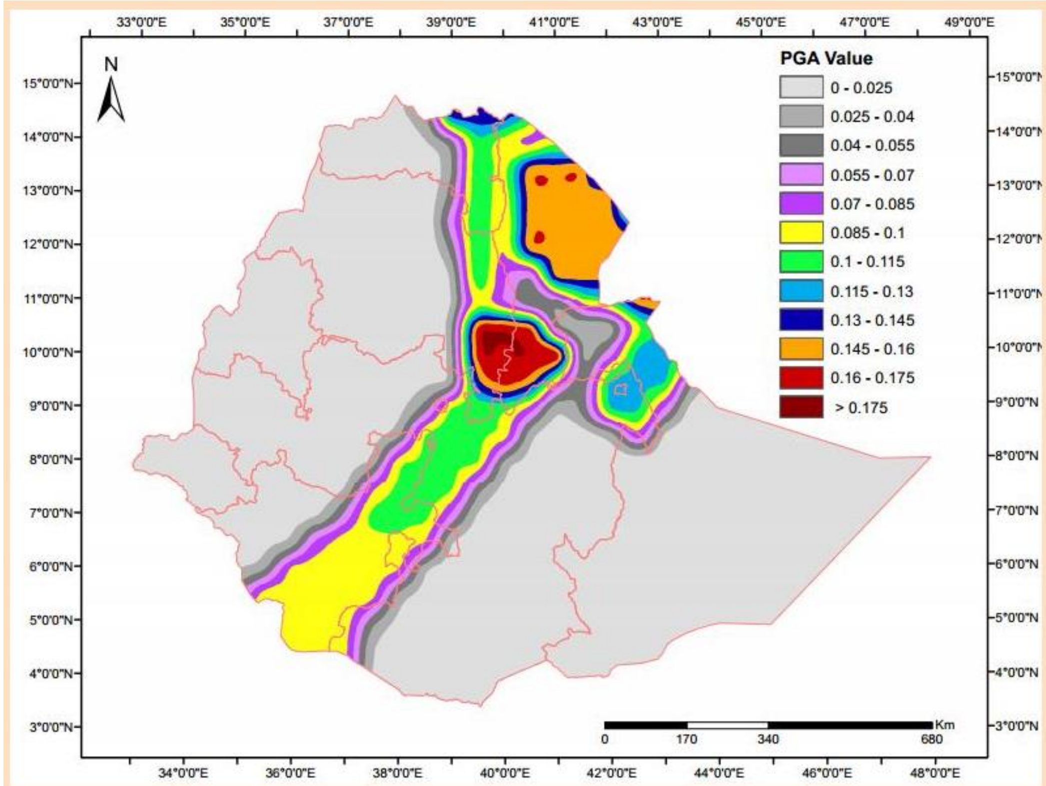


Figure 3.7: Ethiopian seismic hazard map in terms of PGA (ES EN 1998-1:2015)

Table 3.8: Seismic hazard zonation (ES EN 1998-1:2015.)

Region	**R-Code**	**Zone**	**Z-Code**	**Town**	**Longitude E**	**Latitude N**	**Seismic Zone**
Oromia	4	Adama Special Zone	415	Adama	39.2682	8.5386	4

3.8.4.2. peak ground acceleration (PGA)

Adama town is located in seismic zone 4 and peak ground acceleration (PGA) is 0.15 according to the seismic hard map of Ethiopia on the figure above and seismic hazard zonation on table D2 of ES EN 1998-1:2015. The reference peak ground acceleration chosen for seismic zone corresponds to the reference return period of T_{NCR} of the seismic action for no-collapse requirement (or equivalent the reference probability of exceedance in 50 years, P_{NCR})

3.8.4.3. Spectrum type

According to the code, there are two types of spectra based on surface-wave magnitude. If the earthquake that contributes most to the seismic hazard defined for the site for probabilistic hazard assessment has surface-wave velocity magnitude, M_S greater than 5.5, it is recommended that the type 1 spectrum is adopted.

The design of civil engineering structures to be made in the study region should be based on the assumption of a realistic earthquake with a magnitude of M = 7 and intensity of IX Modified Mercalli that correlates with an acceleration of 0.04 to 0.12g. Adama is regarded as a seismically active area concerning earthquake hazards (Freweyni Mekonen, 2016).

According to the literature on seismic hazard history of the research area, type 1 spectrum is adopted have surface-wave velocity magnitude, M_S greater than 5.5.

3.8.4.4. Ground types of study area

Ground types A, B, C, D, and E, classified based on the stratigraphic profiles and parameters as per the code. The parameters considered for ground type classification are shear-wave velocity existing in the top 30 m ($v_{S,30}$), cohesion of the soil (Cu) in kPa and N_{SPT} (blows/30cm).

Multichannel analyses of surface waves reveal the average shear wave velocity in the upper 30m is in the range 270 - 550m/s. According to the NEHRP the soil can be categorized into class C and D, with the major part of the study area falling into site class C (Freweyni Mekonen, 2016).

According to the code and literatures seismic hazard assessment in Adama town, the ground is taken as type C which described in table 3.1 of the code as “Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters.”

3.8.4.5. Behavior factor

The behavior factor, q corresponding the frame system and medium ductility class (DCM) considered in this research.

$$q = q_o k_w \geq 1.5 \quad (3.4)$$

Where:

- q_o: is basic value of behavior factor, depends on the type of structural system and on its irregularity
- k_w: is the factor reflecting the prevailing failure mode in structural system with walls. $k_w = 1$ for frame and frame equivalent dual system.

Since the building is moment resisting frame system in which all lateral load is resisted by frame system through bending of columns and beams, the basic value of behavior factor, q_o corresponding frame system was obtained from table 3.9 according to the code.

Table 3.9: Table basic value of the behavior factor, q_o, for systems regular in elevation

STRUCTURAL TYPE	DCM	DCH
Frame system, Dual system, Coupled wall system	$3.0a_u/a_1$	$4.5a_u/a_1$
Uncoupled wall system	3.0	$4.5a_u/a_1$
Torsionally flexible system	2.0	3.0
Inverted pendulum System	1.5	2.0

Source ES EN 1998-1:2015

Where: a_u/a_1 is multiplication factor

- For regular building in plan with multi story and multi-bay frame, a_u/a_1=1.3
- For irregular building in plan with multi story and multi-bay frame a_u/a_1= average of 1.0 and 1.3 which is equal to 1.15

Then behavior factor, q calculated using the equation 3.4 and the factor given above are:

- ✓ for regular building, q = 3(1.3) = 3.9
- ✓ for irregular building, q = 3(1.15) = 3.45

3.8.4.6. Response spectrum periods

Based on ground type and spectral type response spectrum periods is obtained from the following table 3.10.

Table 3.10: Values of parameters describing Type 1 elastic response spectra.

Ground type	S	T_B(s)	T_C(s)	T_D(s)
A	1	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.4	0.15	0.5	2.0

Accordingly, value of soil factor, S and time periods corresponding spectral type 1 and ground type C for horizontal elastic response spectrum are: S = 1.15, T_B = 0.2sec, T_C = 0.6sec, T_D =2.0sec

3.8.4.7. Response spectrum function and curve

Design spectrum, S_d(T) of horizontal components of the seismic action was defined by the following expressions provided by code:

$$0 \le T \le T_B: \quad S_d(T) = a_g . S . \left[\frac{2}{3} + \frac{T}{T_B} . \left(\frac{2.5}{q} - \frac{2}{3}\right)\right] \tag{3.5}$$

$$T_B \le T \le T_C: \quad S_d(T) = a_g . S . \eta . \frac{2.5}{q} \tag{3.6}$$

$$T_C \le T \le T_D: \quad S_d(T) = \begin{cases} = a_g . S . \frac{2.5}{q} . \left[\frac{T_C}{T}\right] \\ \ge \beta . a_g \end{cases} \tag{3.7}$$

$$T_{CD} \le T: \quad S_d(T) = \begin{cases} = a_g . S . \frac{2.5}{q} . \left[\frac{T_C T_D}{T^2}\right] \\ \ge \beta . a_g \end{cases} \tag{3.8}$$

Where:

- $S_d(T)$ is the design spectrum
- T is the vibration period of a linear single-degree-of-freedom system;
- a_g is the design ground acceleration on type A ground ($a_g = \gamma_I . a_{gR}$)
- T_B is the lower limit of the period of the constant spectral acceleration branch;

- T_C is the upper limit of the period of the constant spectral acceleration branch;
- T_D is the value defining the beginning of the constant displacement response range of the spectrum;
- S is the soil factor;
- η is the damping correction factor with a reference value of η = 1 for 5% viscous
- q is behavior factor;
- β is lower bound factor for horizontal design spectrum, recommended value is 0.2

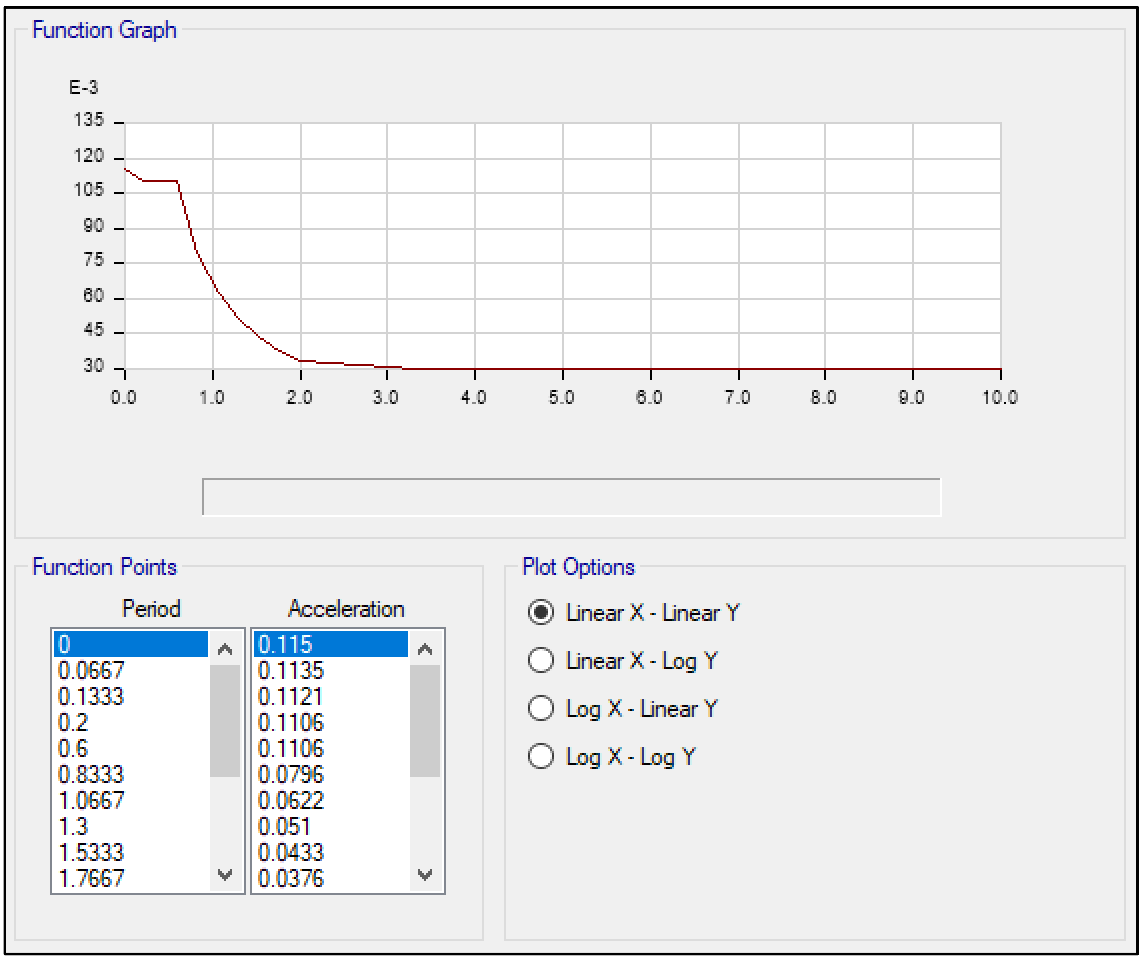


Figure 3.8: Response spectrum curve for regular buildings

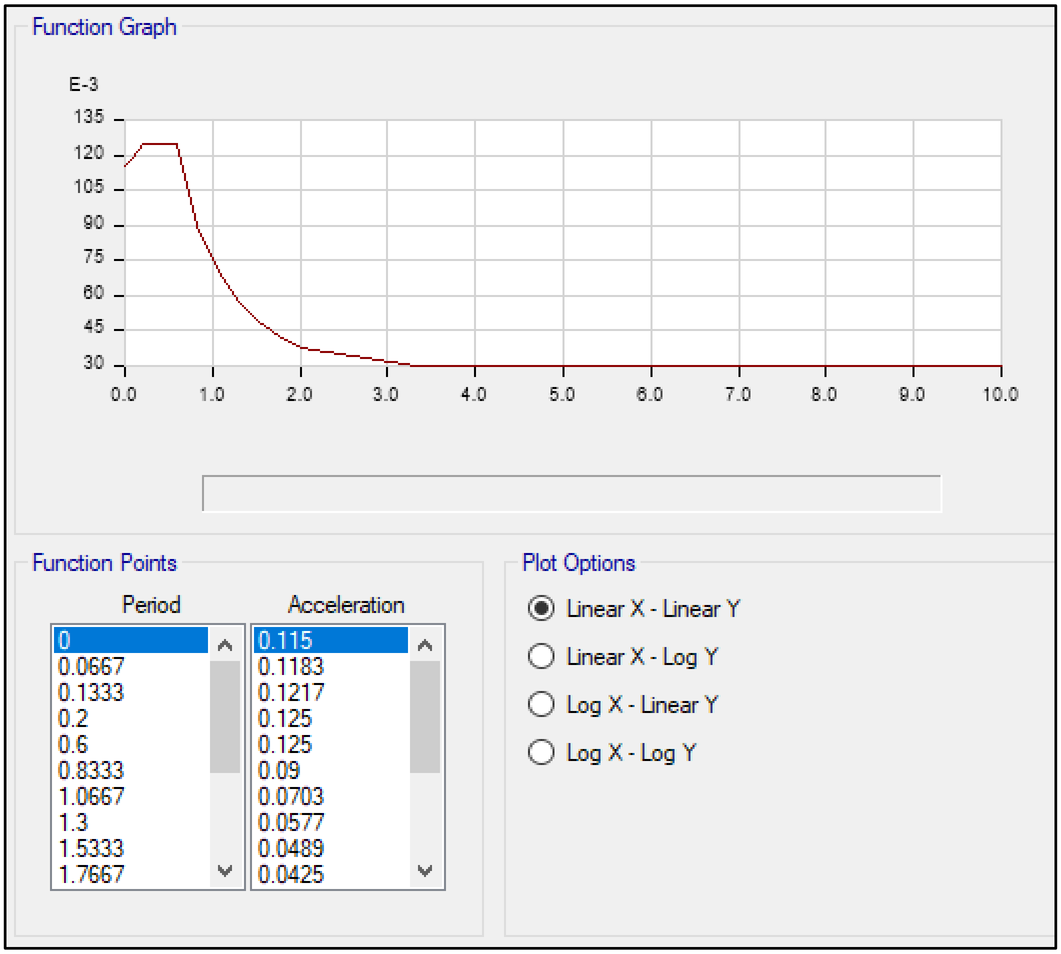


Figure 3.9: Response spectrum curve for irregular buildings

3.8.5. Combination coefficients for variable action

Load combination for seismic analysis is required for mass source definition. An appropriate coefficient of variable action is considered in this research as provided in the design code to be added as additional mass from service load. These coefficients depend on the important factor of each story and the functional class of the building.

$$\sum G_{k,j} + \sum \psi_{Ei} \cdot Q_{k,i} \qquad (3.9)$$

$$\psi_{Ei} = \varphi \cdot \psi_{2i} \qquad (3.10)$$

Where: ψ_{Ei} is combination coefficient of variable action

φ = 1, for Categories D-F*. (Table 4.2 of ES EN 1998-1, 2015)

ψ_{2i} = 0.6, for Categories D. (Table 4.2 of ES EN 1998-1, 2015)

Accordingly, the coefficient for variable action is 0.6.

3.8.6. Modal and load case definition

The total number of modes considered in the response spectrum analysis depends on degrees of freedom at every floor level and direction of the seismic force. Since horizontal seismic force is considered in this research, three modes per floor which are two translation (X and Y-directions) and one rotation in the Z-direction. Accordingly, the total number of modes assigned for the building with eight-story is 24. Eigenvalue analysis method is used as modal analysis method. Since the scope of this study is limited to story displacement, story drift, base shear, base overturning moment, story stiffness and eccentricity response of the structure, result of eigenvalue analysis was not discussed.

load case used for the analysis of the building is response spectrum using proper modal combination methods recommended for a building with a damping ratio greater than one. The CQC methods provide good estimates of maximum response for both regular and irregular structural models as compared to other modal combination methods such as Square Root of Sum Square, Absolute Sum, etc.

CHAPTER FOUR

RESULT AND DISCUSSION

Analysis of the structure is performed according to the methodology discussed in the previous chapter. The response of the structures for selected parameters obtained from the analysis is exported to an excel sheet to evaluate the effect of different staircase types as compared to the building that modeled without staircase. The results are discussed in this chapter in the form of a table, graph, and chart. As discussed earlier, the Load case used for the seismic analysis is elastic response spectrum and response will be discussed in terms of story displacement, story drift, base shear, base overturning moment, and story stiffness. Additionally, the evaluation also included other parameters related to seismic response such as a change in center of mass and stiffness. The analysis is performed in such a way that the effect of location, orientation, and type of staircase on earthquake response is detected.

4.1. Story displacement

Lateral displacement is the most important response of structures under earthquake excitation. Story displacement at every floor level is displayed in graphical form for best illustration of staircase effect on the building modeled without and with the four selected staircase types. Discussion of the analysis result is described as the procedure mentioned in the methodology.

4.1.1. Story displacement of regular building

The regular structure modeled for this research have 7 bays in both X and Y-direction with 4.5m span length. To evaluate the effect of staircase location on seismic response of the structure each stair is provided at the center and corner of the building.

4.1.1.1. Story displacement of regular building with staircase at center(G2)

Mostly staircases provided at building center to best conform with its functional requirement, linking up and down the story for movement of peoples and material. In this section, the effect of a staircase on the seismic response provided at the center of the regular building is discussed in terms of lateral story displacement. It includes a building modeled without a staircase and with four types of staircases. As described earlier in the methodology the selected stairs are:

1. Straight staircase with no landing, S1
2. 180° turning staircase with one landing (Doglegged), S2
3. 90° turning staircase with one landing (L-Shaped), S3
4. 180° turning staircase with two landings(U-Shaped), S4

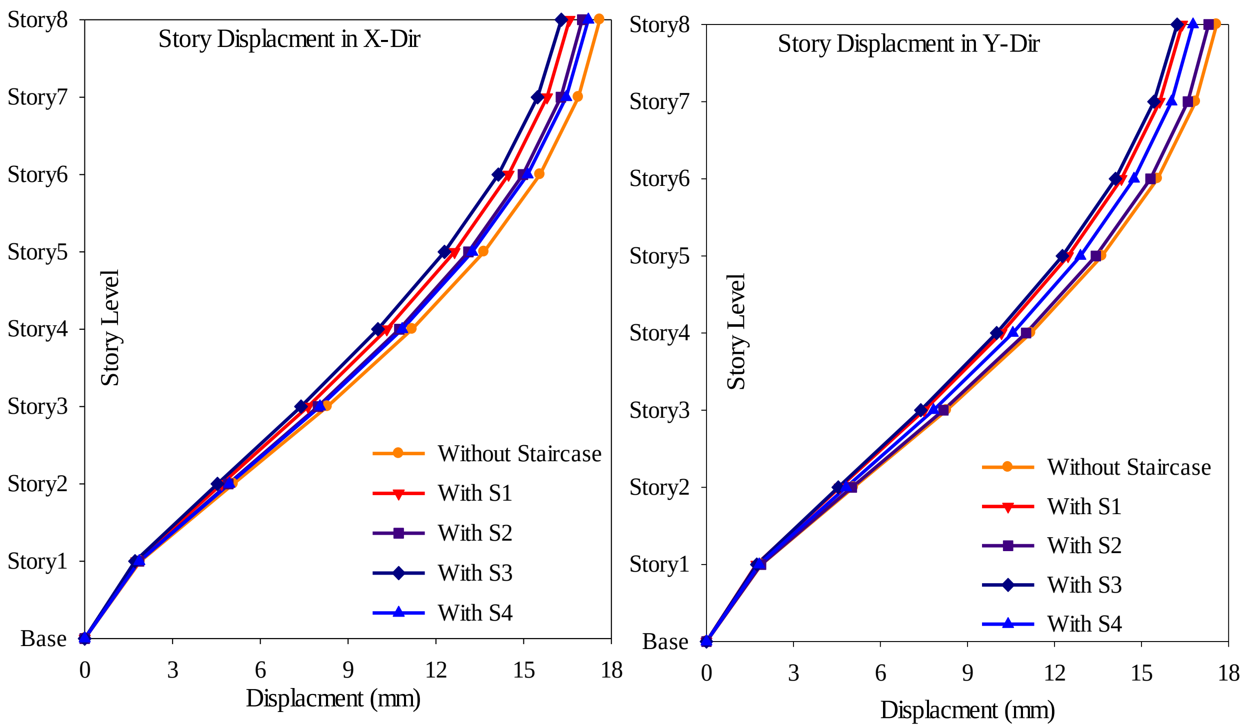


Figure 4.1: Story displacement of regular building with staircase at center(G2)

All stairs on Figure 4.1, are provided parallel to Y-axis in the building. From the tabulated result and graph described in the appendix, the building modeled without a staircase is showing larger story displacement than other buildings modeled with different staircases. This implies staircase will contribute to reducing lateral displacement if provided at the center of structures. The average Percentage change of displacement response at all story levels of buildings modeled with staircase is compared to the one modeled without staircase using equation (4.1).

$$\Delta d_i\% = \left(\frac{d_{wo} - dw}{d_{wo}} \right) 100 \qquad (4.1)$$

$$\Delta d_{avg}\% = \frac{\sum_{i=1}^{8} \Delta d_i\%}{8} \quad (4.2)$$

Where:

- $\Delta d_{avg}\%$ is the average percentage change in displacement of buildings modeled with each staircase type compared to the building without stairs at all story levels.
- $\Delta d_i\%$ is percentage change in displacement of buildings modeled with each staircase type compared to the building without stairs at each story level.
- d_{wo} is the story displacement of the building modeled without staircase.
- d_w is the story displacement of the building modeled with a staircase.

Table 4.1: Average percentage change in displacement for G2

Direction	**With S1**	**With S2**	**With S3**	**With S4**
X-Dir	7.15%	3.49%	9.50%	2.59%
Y-Dir	8.43%	1.35%	9.43%	5.00%

According to table 4.1, the building modeled L-Shaped staircase (S3) is showing maximum displacement reduction (9.50%) whereas, Doglegged staircase (S2) is a relatively minimum displacement variation as compared to a building modeled with other types of stairs. Also, the S3 staircase enhanced almost equal displacement response which is accounted for about 9.50% and 9.43% in X and Y-direction respectively. Story displacement of a building with straight staircase (S1) is also significantly decreased by 7.15% and 8.43% in X and Y-direction respectively as compared to the one modeled without a stair. Then it is structurally recommended to use L-Shaped staircase (S3) staircase if the staircase is to be provided at the center of a regular building to significantly reduce story displacement.

4.1.1.2. Story displacement of regular building with staircase at corner (G3)

Sometimes stairs are provided at the corner if functionally required. Providing staircase at corner significantly affect the seismic response of the building and unless it is properly considered in structural modeling of the building it can cause failure on structural element. in this section, each stair provided at the center in the previous case is provided at a corner without changing their orientation independently in new modeling.

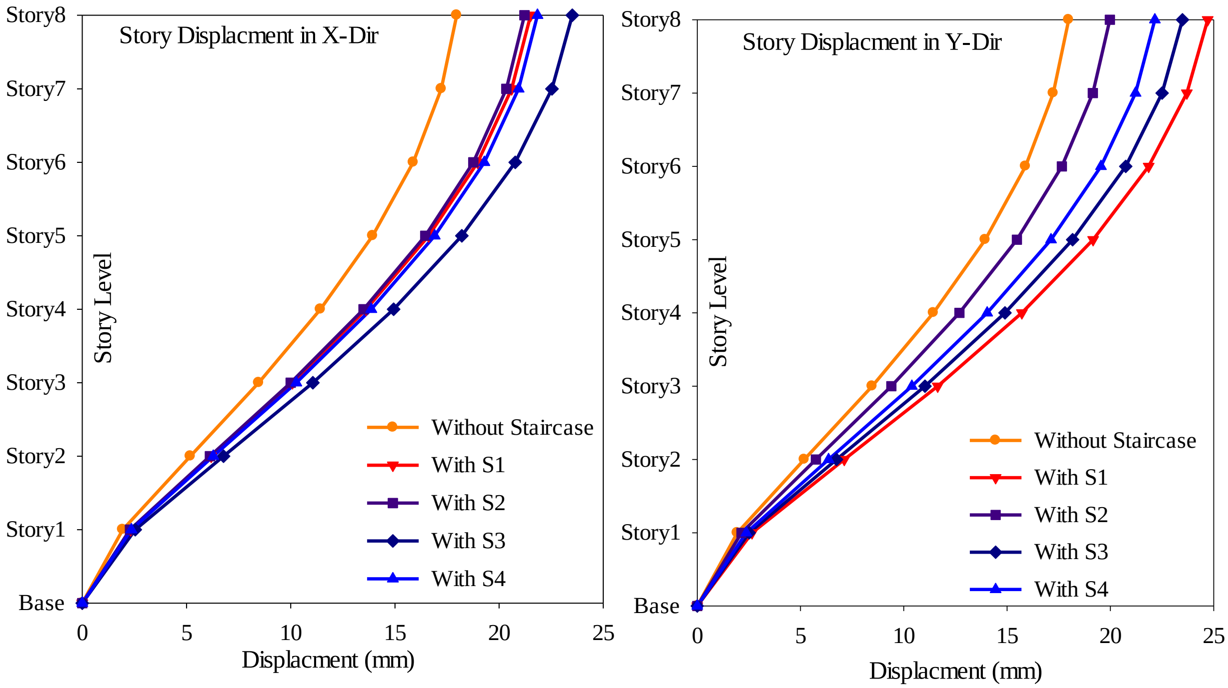


Figure 4.2: Story displacement of regular building with staircase at corner(G3)

As observed from the analysis result of stairs provided at a corner on a regular building(G3) presented in figure 4.2, displacement of the building modeled with different staircases are significantly higher than the one modeled without a staircase. The variation of displacement response of the buildings is more significant than a staircase at the center which necessitates special consideration of staircase effect on a seismic response when it provided at a corner of buildings.

Table 4.2: Average percentage change in displacement G3

Direction	With S1	With S2	With S3	With S4
X-Dir	-19.45%	-18.12%	-30.82%	-21.39%
Y-Dir	-37.41%	-10.96%	-30.30%	-22.85%

According to table 4.2, staircases have negative impact on building response by increasing the story displacement of the building. The negative sign on average percentage change values indicates story displacement of building with staircase is higher than the building without staircase which indicates a negative impact on structural performance. L-Shaped staircase (S3) again shows relatively equal response (30.82% and 30.30%) in both X and

Y-direction while the doglegged (S2) staircase is relatively less affecting the displacement response. The average response variation of straight staircase (S1) in the X and Y direction is 19.45% and 37.41% respectively. These figures show that S1 is more orientation sensitive as compared to the other three types of stairs. Because it extends from story to story without turning which acts as diagonal bracing in the Y direction. U-Shaped staircase (S4) responds nearly average of all staircase considered in both directions.

4.1.2. Story displacement of irregular building

4.1.2.1. Story displacement of irregular building with staircase at center

For irregular structure, it is usually difficult to provide a staircase at the exact location of the building center because of complexity and obstruction from primary structural elements. The irregular structure selected for this research is an 'L' shaped building as explained in methodology. According to this investigation, the stair provided at the center of the irregular building contributed to resistance against lateral story displacement for all staircase types.

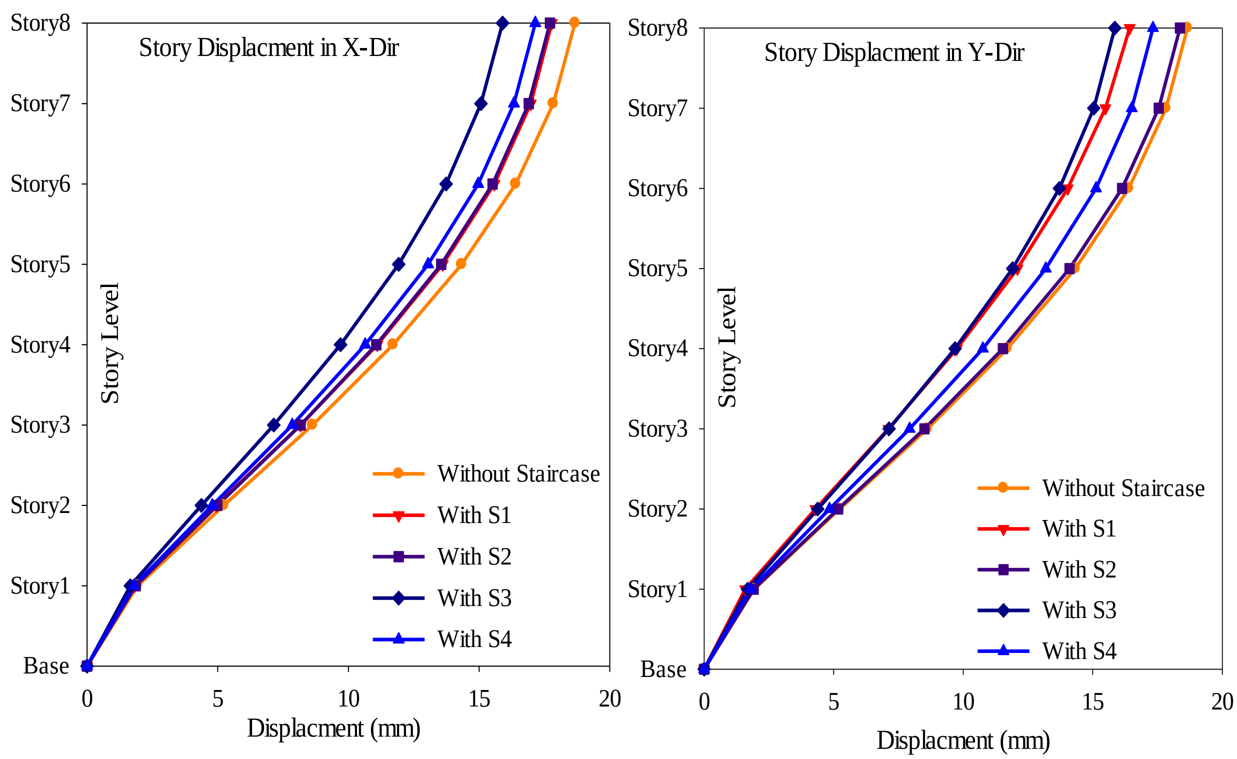


Figure 4.3: Story displacement of irregular building with staircase at center(G4)

Table 4.3: Average percentage change in displacement for G4

Direction	With S1	With S2	With S3	With S4
X-Dir	5.16%	5.05%	16.02%	8.49%
Y-Dir	15.57%	1.30%	15.90%	7.48%

Maximum displacement at top of the building modeled with staircase L-Shaped (S3) is 15.894mm and 15.851mm in X and Y-direction respectively which is minimum as compared to other types of a stair. It also has a nearly equal average percentage variation of displacement response in both directions which is 16.02% and 15.90% in the X and Y-direction respectively. Staircase S2 less affects the seismic response of building. Based on its orientation S2 has relatively higher resistance in the X-direction (in-plane) because it acts as an inclined shear wall. According to the evaluation of average percentage variation in displacement S1 has higher displacement resistance in the Y-direction (15.57%) because its effect is more significant when it acts as diagonal bracing than as inclined shear wall at considered staircase width (1.5m). It should be noted that the width of the staircase is another parameter that affects the seismic response of these structures which is beyond the scope of this research.

Generally, Seismic response result of the stairs has more variation in Y-direction compared to X-direction because of their behavior when acting as a bracing system. According to this investigation, S3 is structurally more recommendable since its response is consistent in both orthogonal direction and it has higher resistance to lateral displacement induced by seismic excitation.

4.1.2.2. Story displacement of irregular building with staircase at corner

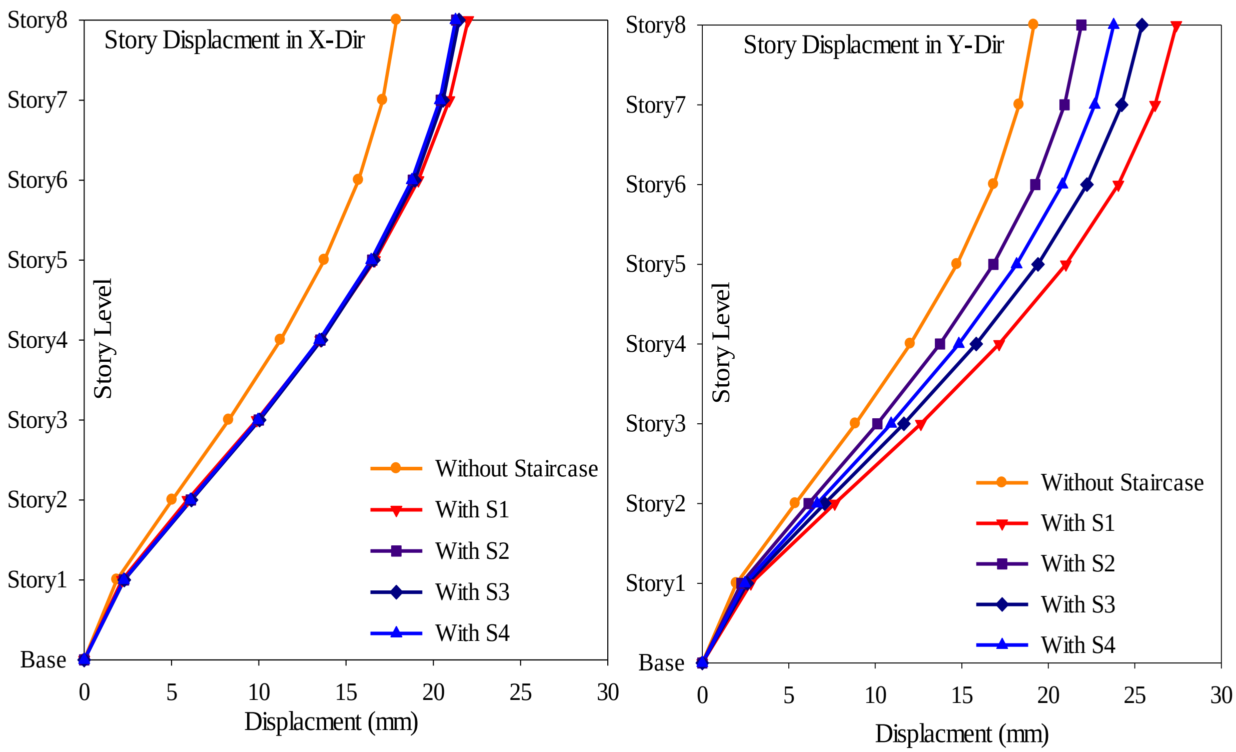


Figure 4.4: Story displacement of irregular building with staircase at corner (G5)

Table 4.4: Average percentage change in displacement for G5

Direction	With S1	With S2	With S3	With S4
X-Dir	-20.21%	-20.34%	-21.03%	-19.88%
Y-Dir	-42.62%	-14.28%	-31.88%	-23.61%

Table 4.4 indicates that, the displacement response of the irregular structure with a staircase at the corner is negative because it reduces the resistance of the building against lateral displacement. As observed from the above graph lateral displacement of all buildings modeled with a staircase is significantly higher than the one modeled without a staircase. Average percentage variation of the response is very close in X-direction (in-plane) than in the Y-direction because all the stair acts differently as a bracing system in the Y-direction. S1 acts as diagonal bracing connecting adjacent floors. S2 acts as K-bracing, S3 braces half story height in both directions whereas S4 braces at one-third of story height.

According to figure 4.4 and table 4.4, it is structurally not recommended to provide straight staircase (S1) and L-Shaped staircase (S3) at the corner of irregular building structures unless proper consideration of their seismic response behavior is made. Since the impact of all stairs is negative when provided at a corner of irregular buildings it is recommended to consider and model them as an integral part of the building structure the same way for beam, column, and slab. S2 stair is relatively less affecting the response of the building against seismic excitation and recommended at corner.

4.1.3. Effect of staircase location on story displacement

The location change in the staircase has a significant effect according to this evaluation. To interpret the effect, relative percent change in displacement is calculated as the following formula. Accordingly, it is concluded as the effect of the doglegged staircase(S2) on seismic response is relatively less than other types of a staircase in both directions. S1 has a larger effect (52.0%) in the Y-direction because it acts as continuous diagonal bracing. S2 affects seismic response nearly equally in both X and Y-directions.

$$\Delta_i\% = \left(\frac{d_{corner} - d_{center}}{d_{center}}\right)100 \qquad (4.3)$$

$$\Delta_{avg}\% = \frac{\sum_{i=1}^{8}\Delta_i\%}{8} \qquad (4.4)$$

Where:

- 'i' is *story* level
- $\Delta_i\%$ is the percentage increase in story displacement with staircase at the corner compared to a staircase at the center in story 'i'
- $\Delta_{avg}\%$ is the average percentage increase in story displacement of all story level
- d_{corner} is story displacement of building with a staircase at the corner
- d_{center} is the story displacement of a building with a staircase at the corner

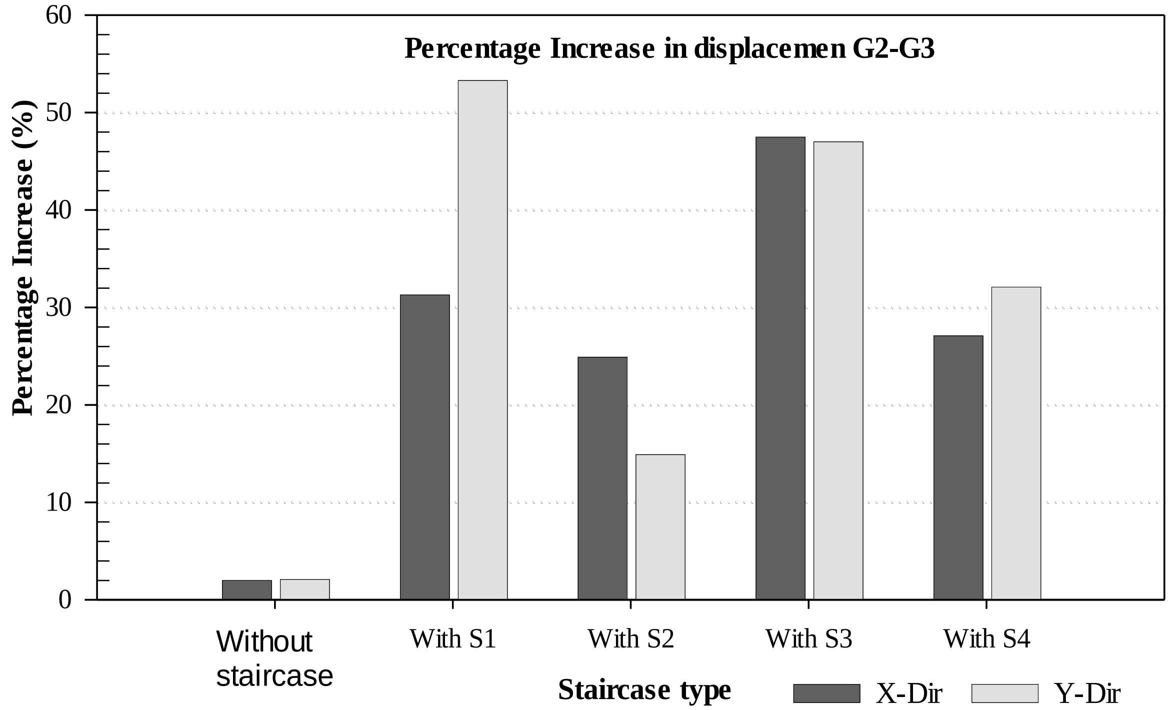


Figure 4.5: Average percentage increase in lateral displacement due to location change from center to corner for regular building.

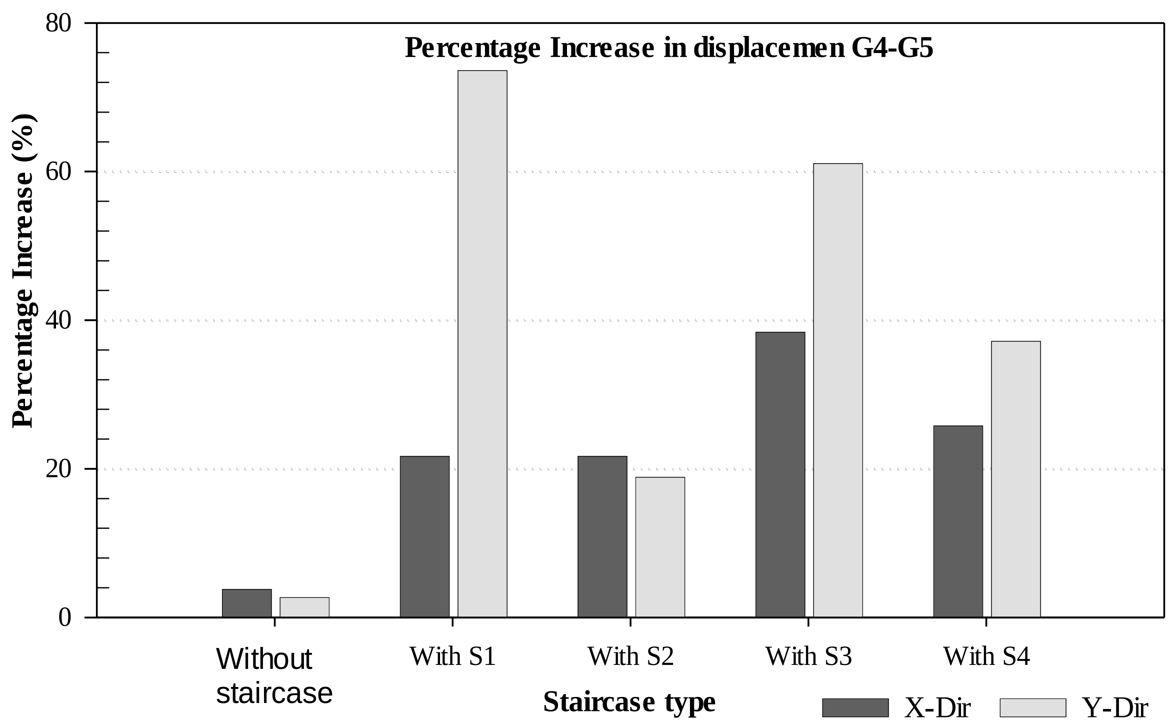


Figure 4.6: Average percentage increase in lateral displacement due to location change from center to corner for irregular building.

Generally, from figure 4.5 and 4.6 lateral displacements of the building with a staircase at a corner is significantly greater than the same building with a staircase at the center of the building. Accordingly, it is structurally recommended to provide a staircase at the center of the building to contribute to the seismic performance of the building structure. The difference is too much significant as observed from the above result discussed by bar charts. Because the effect of a staircase is positive when provided at the center and negative when provided at a corner of the building.

It can be concluded that the S3 staircase is the most promising or preferable when the location of the staircase has to be provided at the center. Because it responds in the same way in both orthogonal directions and have positive impact on displacement response. When the stair location is at a corner, the doglegged staircase (S2) is better since it less affects the displacement response of the structure.

The effect of a staircase on the seismic performance of a building in terms of displacement is very important to select the best staircase type with relatively less lateral displacement. According to this investigation, a building modeled with a staircase at the center of both regular and irregular buildings is significantly less than the same building modeled without a staircase which is a positive effect on seismic response. The lateral displacement of a building with a staircase at the corner is greater than a bare structure modeled without a staircase.

Comparing the four selected staircase types for this research staircase S1 is more displacement resistant in the direction of diagonal bracing than acting as an inclined shear wall in another direction (in-plane). A building modeled with stair S2 is less responsive in terms of lateral story displacement as compared to the other three types of staircases. The lateral displacement response of a building with an S3 staircase is very close in both orthogonal directions except on irregular structure with corner stair. Since lateral displacement depends on the lateral stuffiness of the building structure, the seismic response of irregular buildings with corner stair is inconsistent in the X and Y-direction as it has the same stiffness in both directions.

4.2. Story drift

Story drift is the relative displacement at the top of given story to its bottom of the story. Story drift ratio which described in the following expression is used as dependent variable in this research. story displacement, *d*, and drift basically depend on lateral stiffness and story shear of the building structure. The more the structure is stiff the less it will deflect.

$$Story\ drift = d_{top} - d_{bottom} \tag{4.5}$$

$$Story\ drift\ ratio = \left(\frac{d_{top} - d_{bottom}}{h}\right) \tag{4.6}$$

4.2.1. Story drift of regular building

4.2.1.1. Story drift of regular building with staircase at center

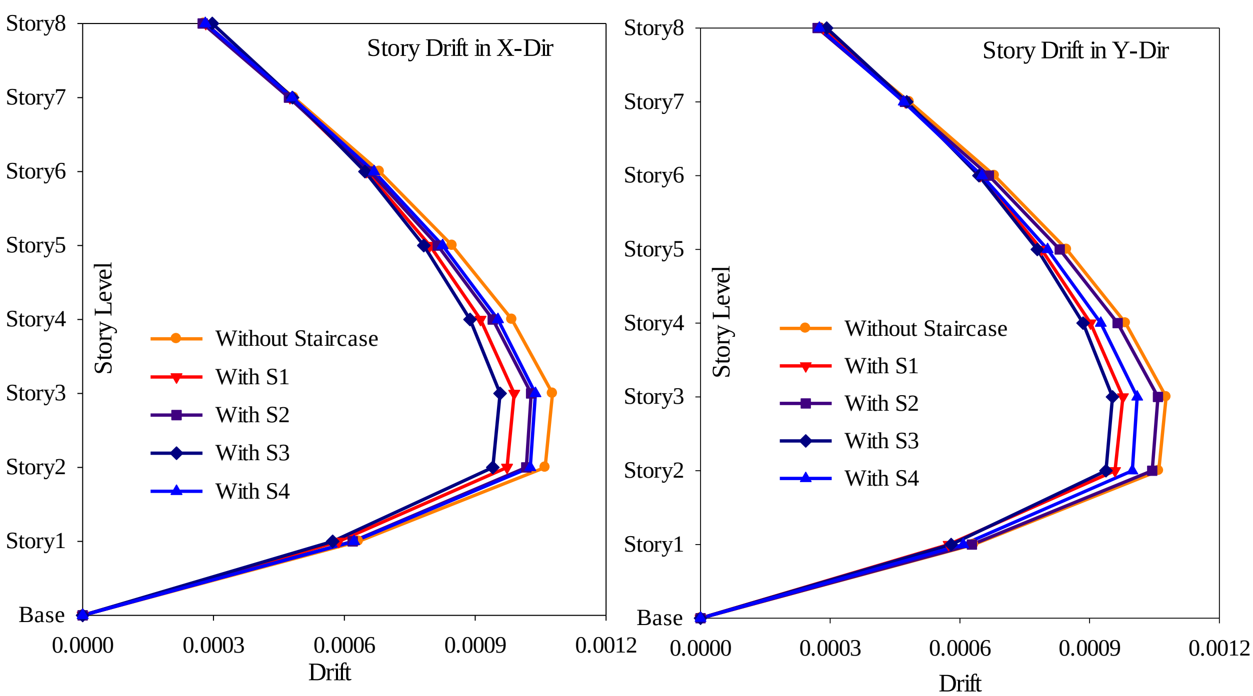


Figure 4.7: Story drift of regular structures with staircase at center(G2)

Table 4.5: Average percentage change in story drift for G2

Direction	With S1	With S2	With S3	With S4
X-Dir	5.15%	3.14%	5.94%	1.93%
Y-Dir	5.92%	1.72%	6.31%	4.31%

Table 4.5 shows the average percentage change in story drift of buildings modeled with staircase relative to the one modeled without staircase. Equation (4.1) and (4.2) is used to calculate the average percentage change in story drift. According to this evaluation, drift of stair S1, S2, S3, and S4 have deviated from the bare structure with 5.15%, 3.14%, 5.94%, and 1.93% in the X-direction respectively. Whereas 5.92%, 1.72%, 6.31% and 4.31% in the Y-direction respectively. This positive percentage change in drift indicates staircase will provide additional drift resistance when provided at the center of the building structure. Among these stairs, S2 less contribute to seismic response whereas S3 has a relatively significant effect.

4.2.1.2. Story drift of regular building with staircase at corner

The group of structural modeling under this case is named G3 which includes regular building modeled with four selected staircase types at corner independently. According to the evaluation of seismic analysis using the response spectrum method, the location of the staircase negatively affects the story drift of the building with stairs provided at a corner.

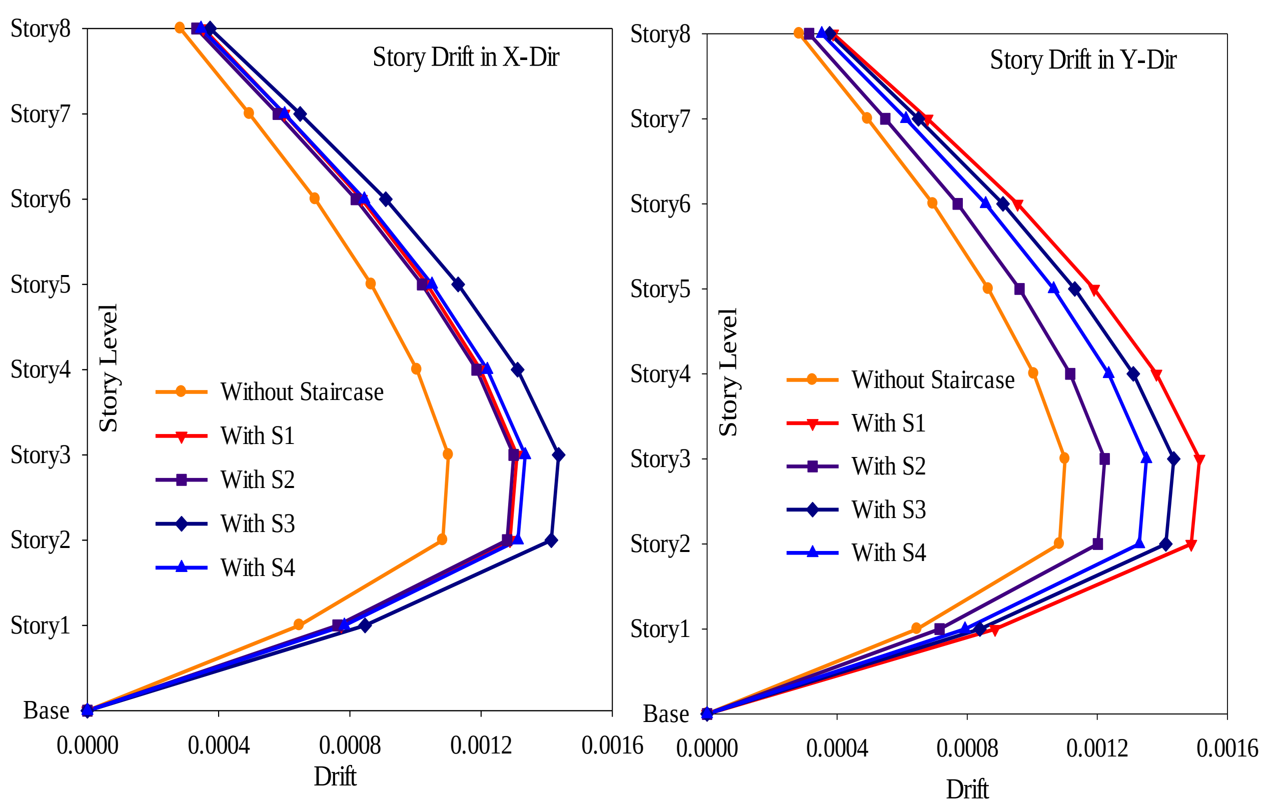


Figure 4.8: Story drift of regular structures with staircase at corner (G3)

Table 4.6: Average percentage change in story drift for G3

Direction	With S1	With S2	With S3	With S4
X-Dir	-20.45%	-17.87%	-30.98%	-21.52%
Y-Dir	-37.34%	-10.95%	-30.90%	-23.25%

As observed from figure 4.8 and table 4.6, the story drift of the buildings modeled with a staircase is significantly higher than the building modeled without a staircase. The minus sign in average percentage variation of story drift indicates that the staircase has a negative effect on the seismic performance of a building. Accordingly, average percentage deviation of drift due to S1, S2, S3 and S4 is -20.45%, -17.87%, -30.98% and -21.52% in X-direction whereas -37.34%, -10.95%, -30.90% and -23.25% in Y-direction respectively. These figures imply that S3 and S1 are not structurally recommended as the best staircase type to be provided at a corner of buildings.

4.2.2. Story drift of irregular building

4.2.2.1. Story drift of irregular building with staircase at center

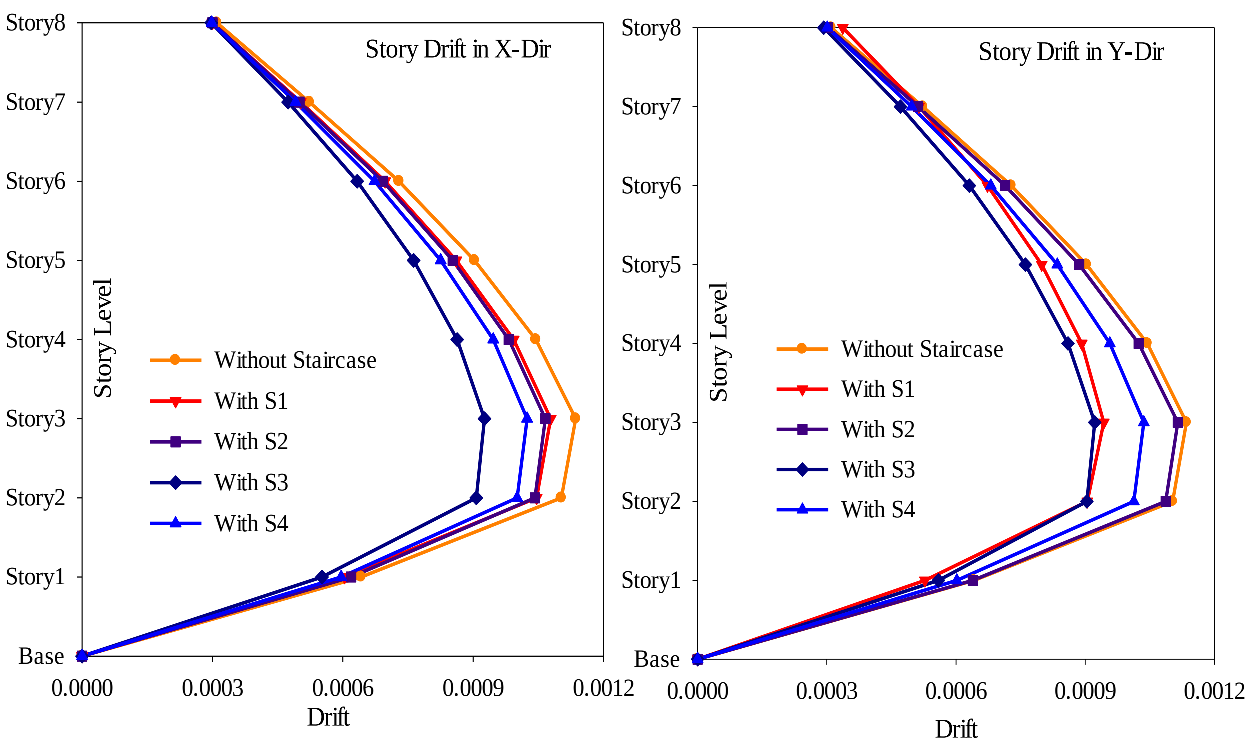


Figure 4.9: Story drift of irregular structures with staircase at center(G4)

Table 4.7: Average percentage change in story drift for G4

Direction	With S1	With S2	With S3	With S4
X-Dir	4.63%	4.91%	13.71%	7.73%
Y-Dir	9.90%	1.71%	13.97%	6.65%

The story drift of irregular buildings modeled with a staircase at the center (G4) is less than the bare structure (without staircase). This is obviously due to the contribution of a staircase to the lateral stiffness of the building which reduces lateral displacement. From the graph of story drift, the building with S3 is less than the other three types of staircase. This implies percentage change in story drift of S3 compared to the one without staircase is higher, 13.71% and 13.97% in the X and Y-direction respectively. The response of S4 is relatively close to each other in both orthogonal directions next to the S3 stair. The average percentage change in story drift in X-direction of S1 and S2 is 4.63% and 4.91% respectively which is very close because in plan action with the same staircase width (1.5m). since the stairs reaction as a bracing system is different in the Y-direction story drift is more variant as compared to in the X-direction.

4.2.2.2. Story drift of irregular building with staircase at corner

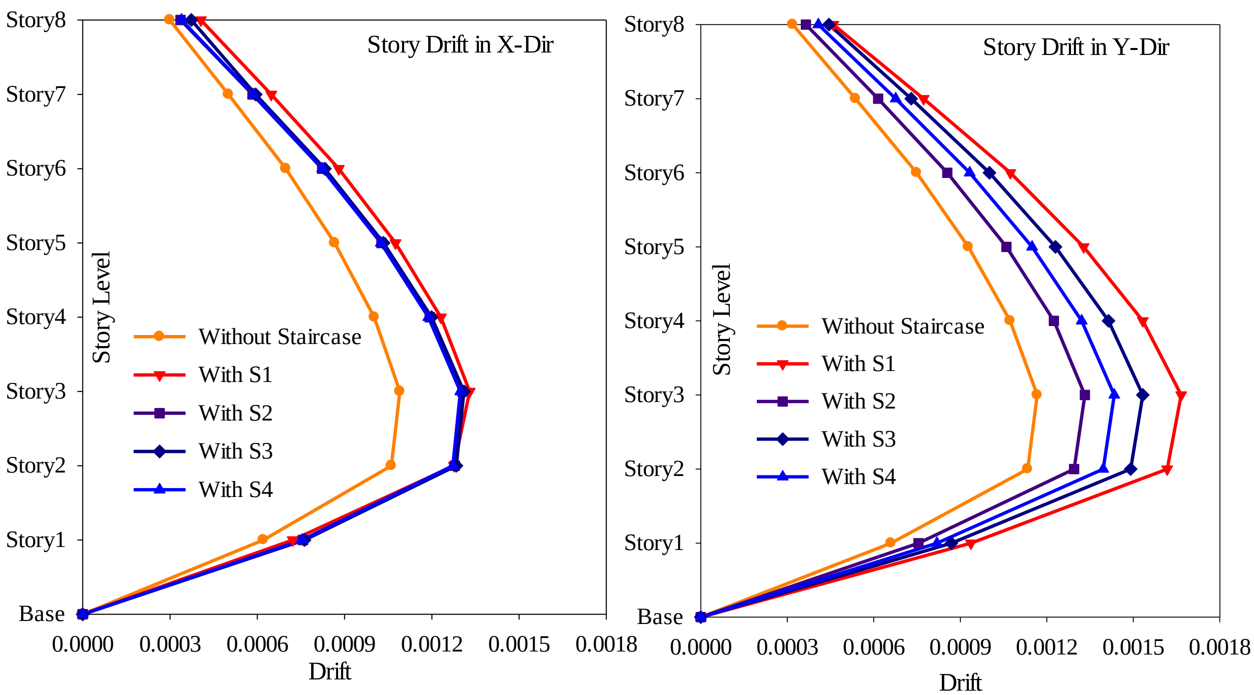


Figure 4.10: Story drift of irregular structures with staircase at corner(G5)

Table 4.8: Average percentage change in story drift for G5

Direction	With S1	With S2	With S3	With S4
X-Dir	-24.64%	-18.38%	-20.74%	-18.24%
Y-Dir	-43.18%	-14.33%	-33.55%	-24.47%

This group of modeling is named G5 as described in the methodology of this research. From the graph of the story drift staircase negatively affects building response against seismic action by changing stiffness center when provided at a corner of the building. According to the analysis of seismic response using response spectrum method on irregular building with a staircase at corner story drift of building with staircase significantly higher than that of the same building structure without a staircase. Story drift with S1 is much higher (43.18%) in the Y-direction.

4.2.3. Effect of staircase location on story drift

As described earlier staircase type and orientation in orthogonal direction affects the seismic response of the building and needs to be modeled along with other primary structural members such as beam, column, and slab. In this section effect of staircase location on seismic response is described in percentage increase as compared to story drift of building with stair at the center is presented in graphical form.

$$\Delta dr_i\% = \left(\frac{dr_{corner} - dr_{center}}{dr_{center}}\right)100 \qquad (4.7)$$

$$\Delta dr_{avg}\% = \frac{\sum_{i=1}^{8} \Delta dr_i}{8} \qquad (4.8)$$

Where:

- ‘i’ is *story* level
- $\Delta dr_i\%$ is the percentage increase in story drift with the staircase at a corner compared to the staircase at a center in story ‘i’
- $\Delta dr_{avg}\%$ is the average percentage increase in the story drift of all story levels
- dr_{corner} is the story drift of a building with the staircase at a corner
- dr_{center} is the story drift of a building with the staircase at a corner

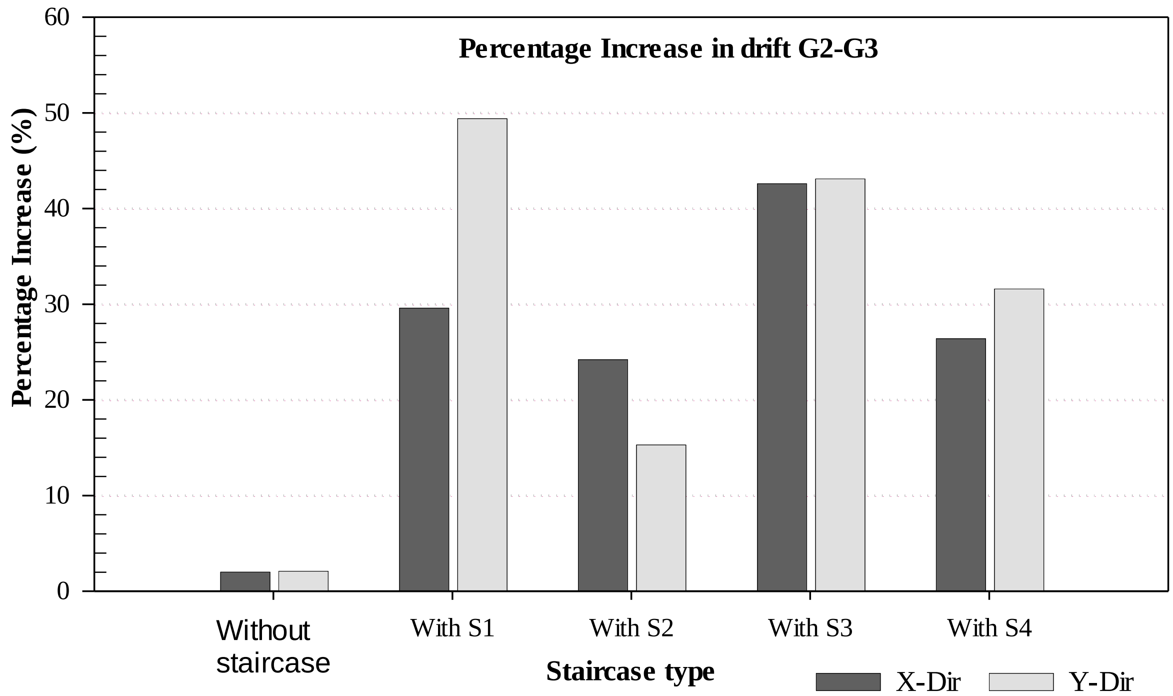


Figure 4.11: Average percentage increase in story drift of regular building with a staircase at corner and center as a reference to the staircase at the center of the building

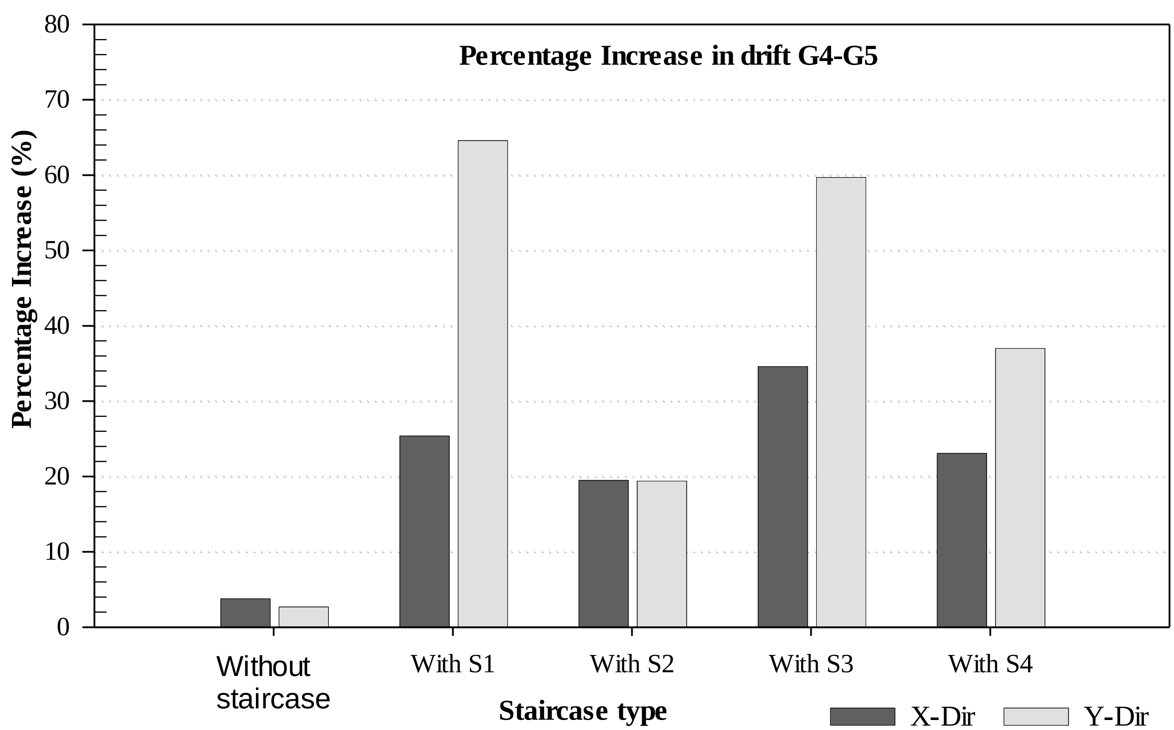


Figure 4.12: Average percentage increase in story drift of regular building with a staircase at corner and center as a reference to the staircase at the center of the building

According to the evaluation of staircase location on the seismic response in terms of story drift, stair S1 significantly affects story drift in X-direction on regular and irregular building with 49.5% and 64.7% respectively. Response associated with the regular building is more preferable to select the structurally best type of staircase for any building. This is because the stiffness center of the irregular building is difficult to properly locate as compared to a regular building. The location of stairs affects regular and irregular buildings relatively closer as compared to other types of staircase.

4.3. Base shear

Base shear is the summation of all story shear at the base of the building which is primarily associated with the mass source and acceleration response spectrum of the structure. According to this research, the base shear of each modeling case is analyzed by ETABS V.18 software and exported to excel for further investigation of staircase effect on seismic response in terms of base shear. Percentage variation due to assigning different staircase type as compared to bare building structure without staircase is presented in this section.

4.3.1. Base shear of regular building

4.3.1.1. Base shear of regular building with staircase at center

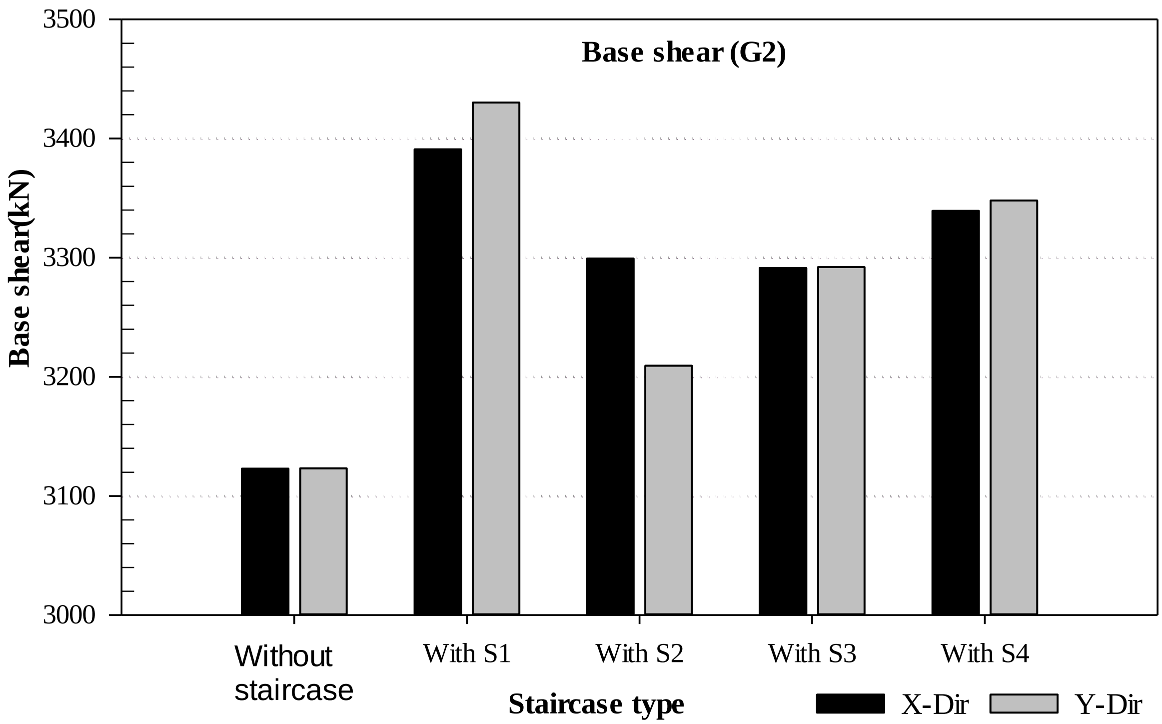


Figure 4.13: Base shear of regular structures with staircase at center(G2)

Table 4.9: Average percentage change in base shear for G2

Direction	With S1	With S2	With S3	With S4
X-Dir	8.58%	5.65%	5.40%	6.93%
Y-Dir	9.83%	2.76%	5.41%	7.20%

This group of modeling(G2) consists of four buildings modeled with staircase and the same building without staircase with an equivalent opening having the same size of plan to each respective staircase type. Base shear of building with staircase is slightly greater than the building without staircase due to addition of staircase mass and the associated portion of live load. Accordingly, the base shear of the building with S1 is 3390.9kN and 3430.2kN in X and Y-direction which is 8.58% and 9.83% deviated from the building modeled without staircase respectively. S3 has almost equal base shear in both orthogonal directions with equal percentage (5.4%) variation from building without a stair. S2 has 3299.3kN and 3209.4kN which constitute 5.65% and 2.76% in the X and Y-direction respectively. These figures indicate that S3 type of staircase is more preferable to be provided at a center of a regular structure due to its minimum and balanced response in both orthogonal directions.

4.3.1.2. Base shear of regular building with staircase at corner

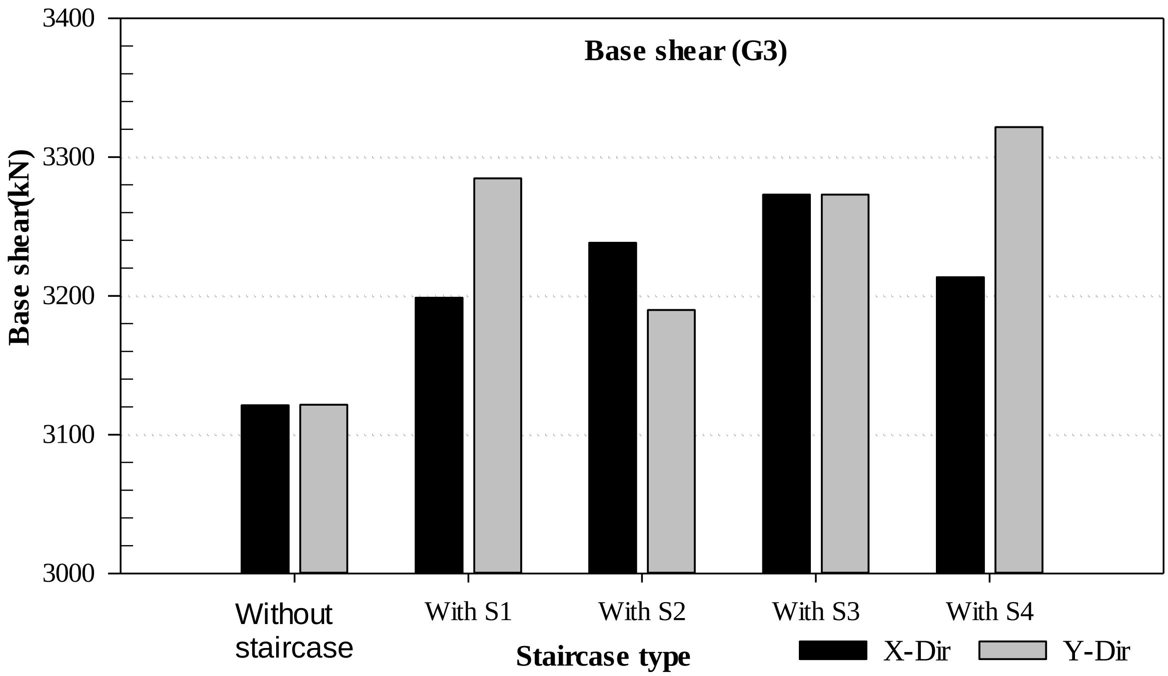


Figure 4.14: Base shear of regular structures with staircase at corner(G3)

Table 4.10: Average percentage change in base shear for G3

Direction	With S1	With S2	With S3	With S4
X-Dir	2.48%	3.75%	4.85%	2.95%
Y-Dir	5.22%	2.18%	4.85%	6.41%

Analysis result of the G3 group shows that base shear due to S4 is relatively higher(3321.5kN) than the other three types of staircases. But, the Effect of change in base shear is not exaggerated as the effect in terms of story displacement and story drift. The regular building is easier to provide a staircase at the location where it structurally advantageous as its center of stiffness and mass approaches each other. According to this evaluation percentage change in base shear response due to S2 as compared to the bare building structure is 3.75% and 2.18% in the X and Y-direction respectively which makes it a suitable type of staircase type at corner since relatively minimum base shear response. Response variation as compared to the orientation of each staircase type indicates that S1 and S4 in the Y-direction with percentage variation 5.22% and 6.41% respectively are higher and need special attention during the design of buildings for seismic action. Analysis result of stairs at the corner on regular building with S3 stair has identical (4.85%) response variation on X and Y-direction. It is wise to properly utilize the structural advantage of each staircase type and integrate their possible combined effects due to other secondary structural members such as a shear wall in high seismic areas.

4.3.2. Base shear of irregular building

4.3.2.1. Base shear of irregular building with staircase at center

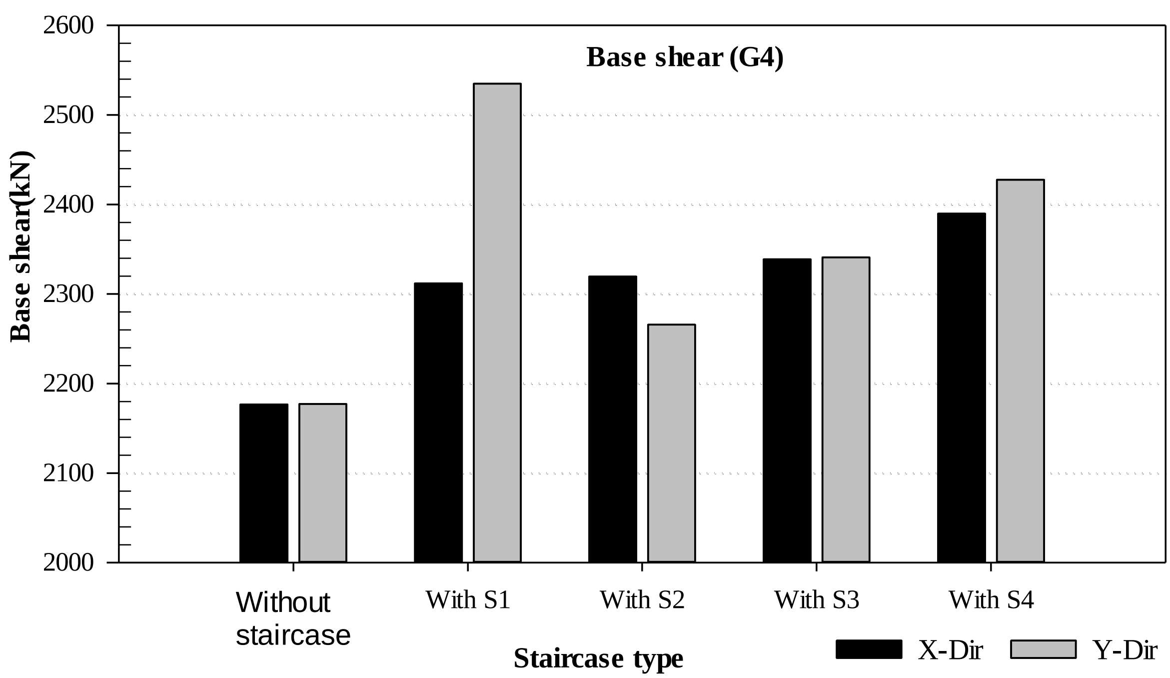


Figure 4.15: Base shear of irregular structures with staircase at center(G4)

Table 4.11: Average percentage change in base shear for G4

Direction	With S1	With S2	With S3	With S4
X-Dir	6.21%	6.57%	7.45%	9.80%
Y-Dir	16.43%	4.07%	7.52%	11.50%

Base shear response of irregular building modeled with a staircase at the center (G4) presented in bar chart form indicates that S1 stair has maximum(2534.9kN) which constitute 16.43% percentage variation from building without staircase in the Y direction. Percentage variation in base shear for S2 is 6.57% and 4.07% in X and Y-direction respectively which is relatively minimum of all staircase types under this investigation. 90^o turning staircase with one landing responds 2338.8kN and 2340.9kN in X and Y-direction respectively which deviated from the building without staircase with nearly equal percentage variation in both directions. It is recommended to minimize possible base shear to reduce the seismic impact on a building. Even though S2 has a relatively minimum response it has considerable variation in the X and Y-direction. Accordingly, S3 is the most convenient staircase type to be provided at the center of a building due to balanced response in both orthogonal directions.

4.3.2.2. Base shear of irregular structure with staircase at corner

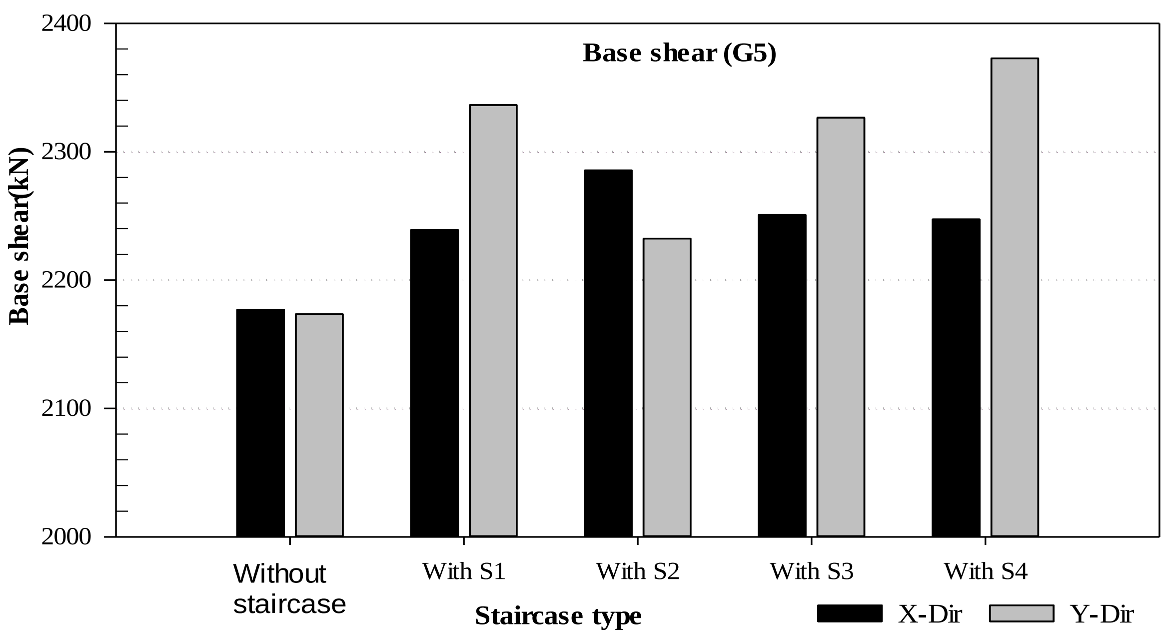


Figure 4.16: Base shear of irregular structures with staircase at corner(G5)

Table 4.12: Average percentage change in base shear for G5

Direction	With S1	With S2	With S3	With S4
X-Dir	2.85%	4.99%	3.39%	3.24%
Y-Dir	7.49%	2.71%	7.04%	9.17%

According to the base shear analysis result of an irregular building with a staircase at a corner location, S4 has a maximum(2372.8kN) with a 9.17% percentage variation from the bare building without a staircase. Base shear response of building with a staircase in the X-direction is less deviated from the bare structure without staircase as compared to the response in the Y-direction.

4.4. Base overturning moment

Base overturning moment is taken as the sum of the moment on a story at the bottom of the building. This parameter of seismic response depends on the story shear and story height of the building. Moment is the product of force and distance (lever-arm) vectored perpendicular direction to each other. This implies that story shear in X-direction produces moment about Y-direction whereas the lever arm is vertical (Z-direction). This implies that the product force and distance in which they are perpendicular gives moment in the third perpendicular direction.

4.4.1. Base overturning moment of regular building

4.4.1.1. Base overturning moment of regular building with staircase at center

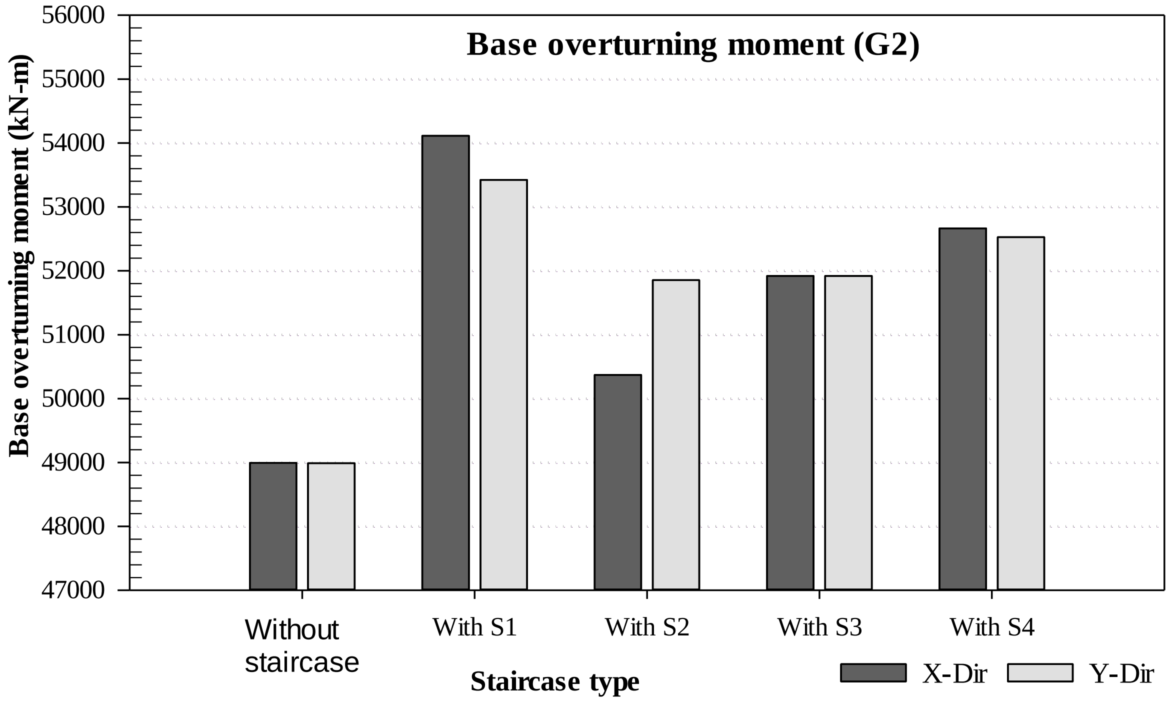


Figure 4.17: Base overturning moment of regular structures with staircase at center(G2)

Table 4.13: Average percentage change in base overturning moment for G2

Direction	With S1	With S2	With S3	With S4
X-Dir	10.45%	2.80%	5.97%	7.49%
Y-Dir	9.05%	5.85%	5.98%	7.22%

A group of this modeling is named G2. The overturning moment of building with staircase S1 is maximum (54114kN-m and 53422kN-m) in the X and Y-direction with a percentage variation of 10.45% and 9.05% respectively. These values of overturning moment are associated with the base shear response of building. Overturning moment variation as compared to the building without staircase for S3(5.97% and 5.98%) is nearly the same in either direction as discussed in the previous seismic response parameter.

4.4.1.2. Base overturning moment of regular building with staircase at corner

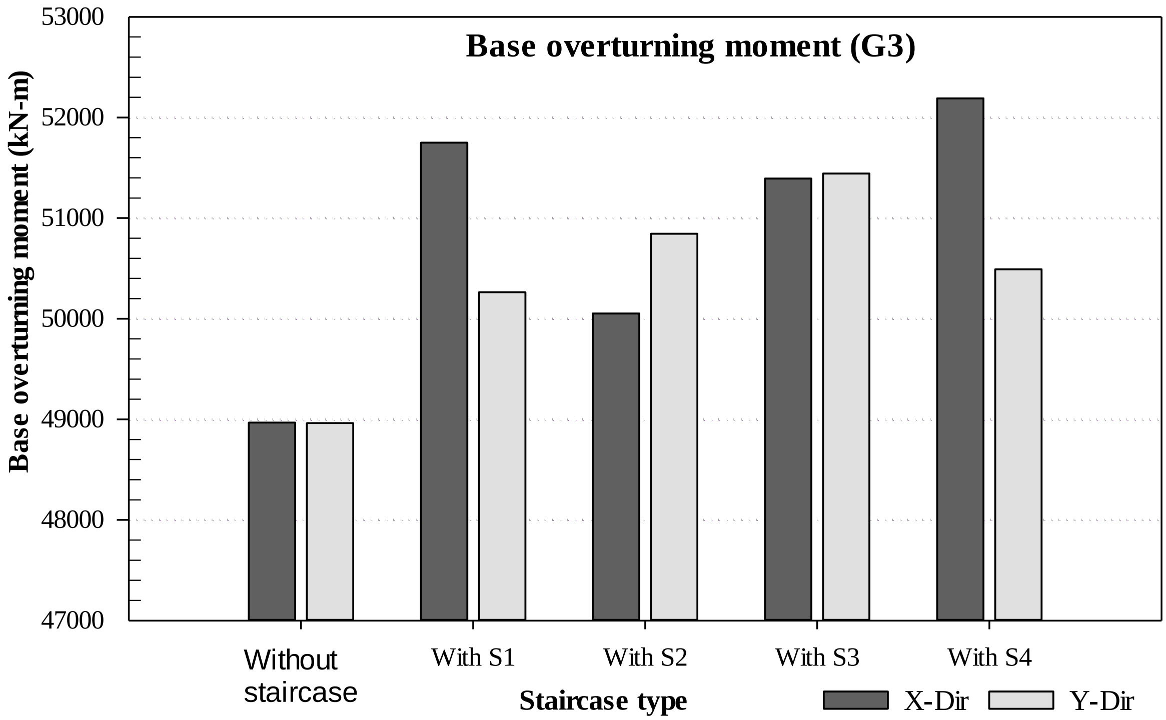


Figure 4.18: Base overturning moment of regular structures with staircase at corner(G3)

Table 4.14: Average percentage change in base overturning moment for G3

Direction	With S1	With S2	With S3	With S4
X-Dir	5.68%	2.22%	4.95%	6.58%
Y-Dir	2.66%	3.85%	5.07%	3.12%

According to this analysis result, the overturning moment of S4 in the X-direction(52189kN-m) is maximum and constitutes a 6.58% percentage difference from the building without staircase in the respective direction. S2 is responding relatively minimum(50053kN-m) in the X-direction which is the in-plane side for the doglegged staircase. Since the overturning moment is mainly dependent on the seismic weight of the structure, it could be difficult to be conclusive only from this seismic response parameter alone unless simply indicating the staircase with the minimum overturning moment.

4.4.2. Base overturning moment of irregular building

4.4.2.1. Base overturning moment of irregular building with staircase at center

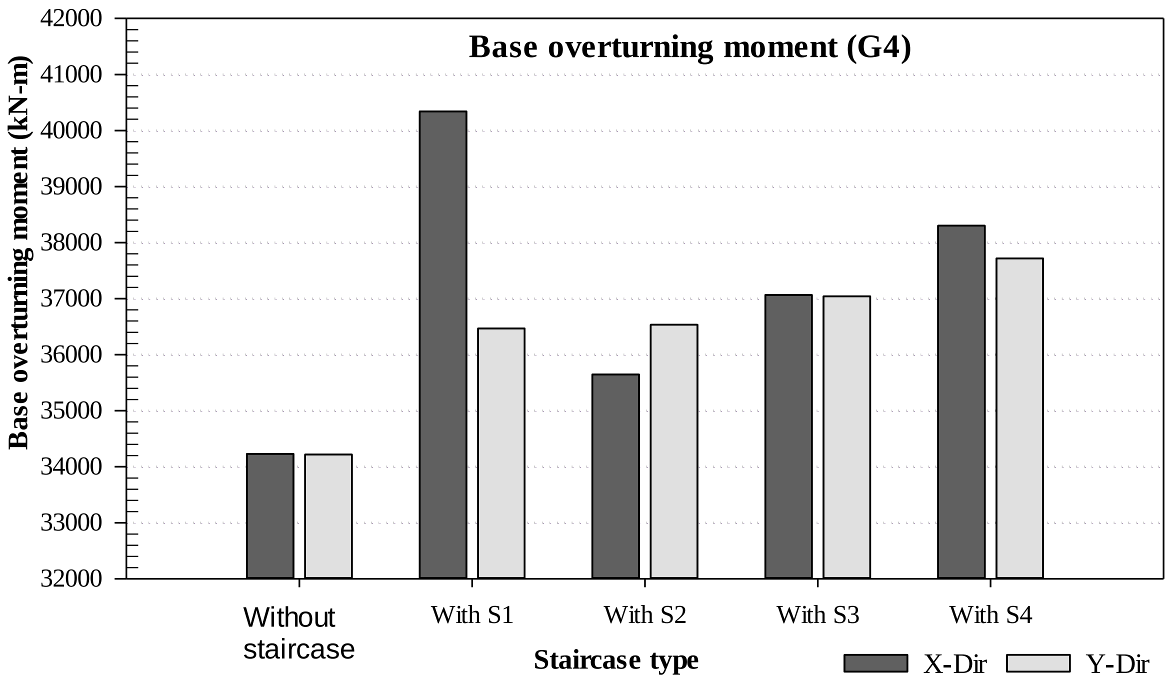


Figure 4.19: Base overturning moment of irregular structures with staircase at center(G4)

Table 4.15: Average percentage change in base overturning moment for G4

Direction	With S1	With S2	With S3	With S4
X-Dir	17.85%	4.14%	8.29%	11.90%
Y-Dir	6.57%	6.76%	8.25%	10.23%

Overturning moment of building with S1 in X-direction that generated due to story shear in the Y-direction is maximum(403401kN-m) of all response effect which is 17.85% increased from an irregular building without staircase at the center. When the S4 staircase is used, the percentage increase in the response of X and Y-direction is also maximum with 11.90% and 10.23% respectively whereas building with S3 stair's response increase by 8.29% and 8.25% in X and Y-direction respectively.

4.4.2.2. Base overturning moment of irregular building with staircase at corner

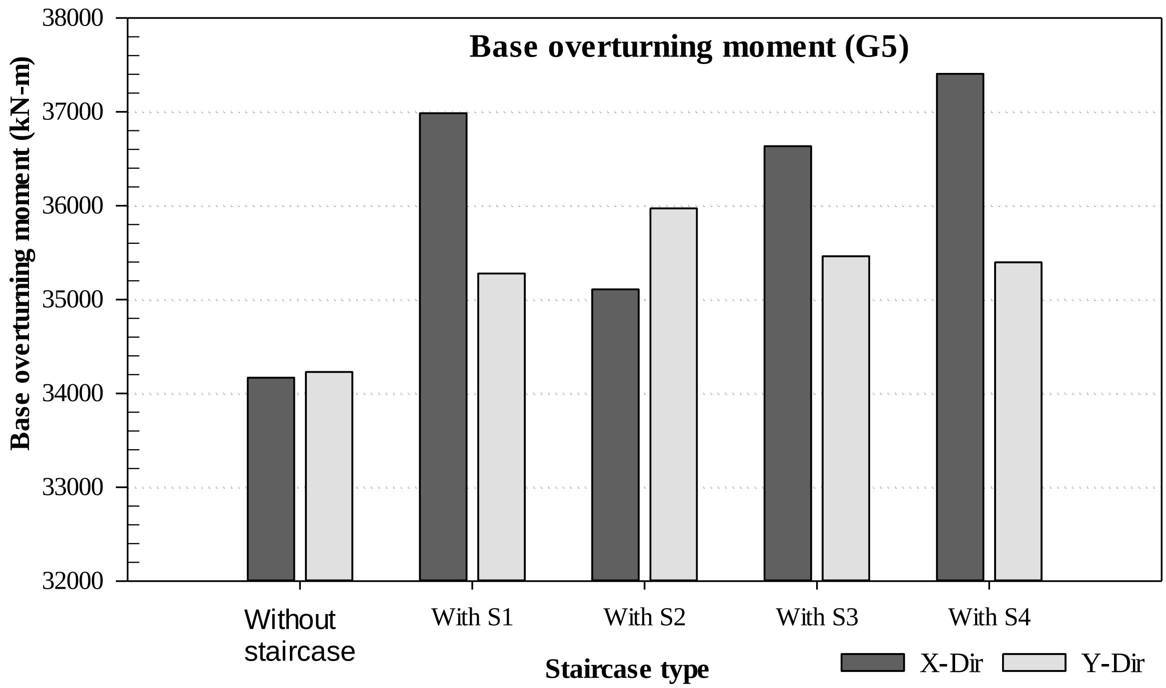


Figure 4.20: Base overturning moment of irregular structures with staircase at corner(G5)

Table 4.16: Average percentage change in base overturning moment for G5

Direction	With S1	With S2	With S3	With S4
X-Dir	8.25%	2.75%	7.22%	9.48%
Y-Dir	3.06%	5.09%	3.60%	3.41%

According to figure 4.20 and table 4.16, overturning moment of building with S4 in X-direction is maximum with a percentage increase of 9.48% from the building modeled without a staircase. In some irregular structures are difficult to know the center of rigidity and center of mass to provide a staircase at a structurally suitable location. In such cases, it is recommended to provide an S2 type of staircase because it relatively less affects the seismic response of the building as compared to other types of staircase.

4.5. Story stiffness and Eccentricity

4.5.1. Story stiffness

Stiffness is the rigidity of structural elements that depend on the material properties and geometric configuration of each structural member. It can also be defined as the resistance of elements against deformation under the action of an applied force. The more the structure is rigid the less it will deflect. ETABS uses the finite element method to calculate story stiffness. According to the findings of this research, the staircase affects the story stiffness of a building either positively or negatively. Those staircases provide at center increased stiffness of the building both on regular and irregular building structures whereas staircases provided at a corner of the building caused stiffness irregularity.

$$\Delta K_i\% = \left(\frac{Kw - Kwo}{Kwo}\right)100 \tag{4.9}$$

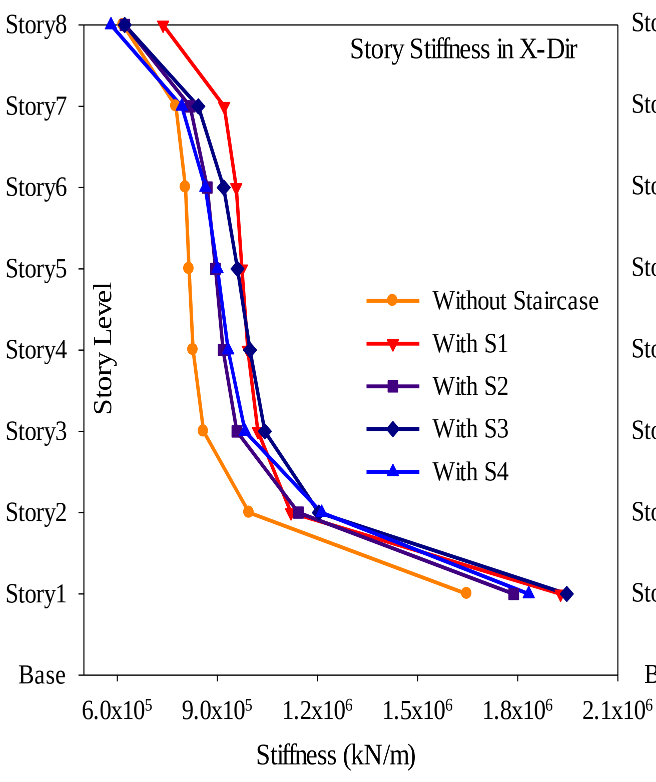
$$\Delta K_{avg}\% = \frac{\sum_{i=1}^{8} \Delta K_i\%}{8} \tag{4.10}$$

Where:

- 'i' is *story* level
- $\Delta K_i\%$ is the percentage change in story stiffness of the building modeled with staircase as compared to the building modeled without a staircase in story 'i'
- $\Delta K_{avg}\%$ is the average percentage change in a story stiffness of all story levels
- K_w is the stiffness of a building modeled with a staircase.
- K_{wo} is the stiffness of the building modeled without a staircase.

Table 4.17: Average percentage change in a story stiffness

Modeling Group	Direction	Average percentage change Stiffness With staircase			
		With S1	**With S2**	**With S3**	**With S4**
G2	X-Dir	18.11%	8.77%	15.33%	9.31%
	Y-Dir	20.36%	3.48%	14.73%	10.06%
G3	X-Dir	-4.60%	3.80%	-3.83%	0.16%
	Y-Dir	-2.41%	0.16%	-3.92%	1.22%
G4	X-Dir	12.66%	11.21%	23.09%	13.80%
	Y-Dir	28.86%	6.04%	22.98%	14.87%
G5	X-Dir	-4.22%	6.85%	1.96%	4.99%
	Y-Dir	-7.96%	-3.76%	-5.82%	-0.87%



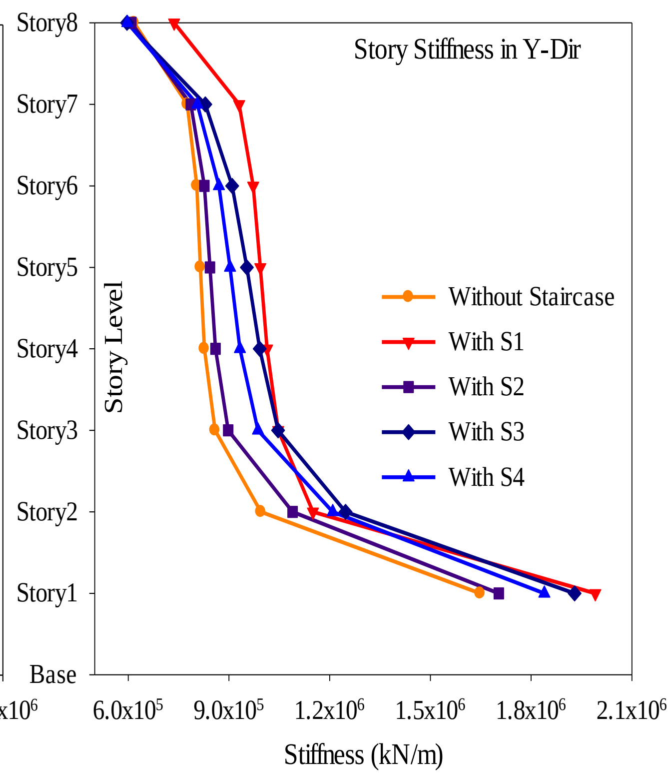


Figure 4.21: Story stiffness of regular structures with staircase at center(G2)

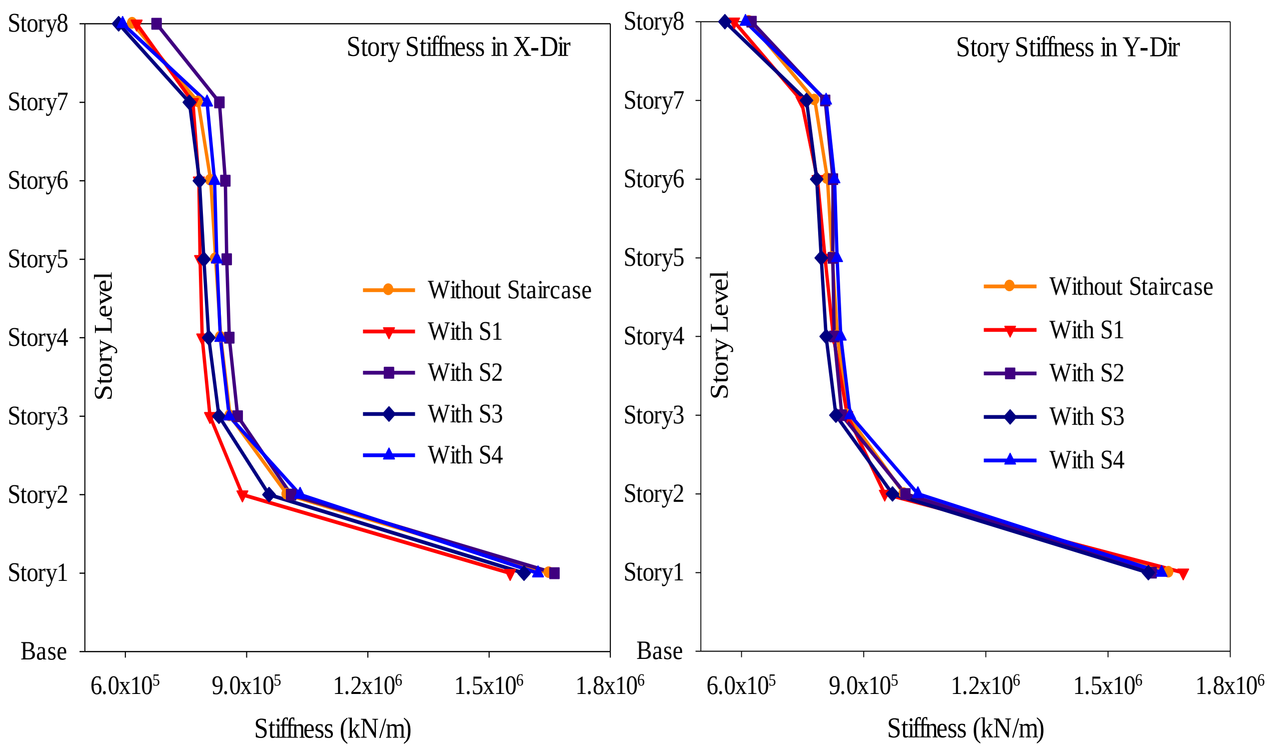


Figure 4.22: Story stiffness of regular structures with staircase at corner(G3)

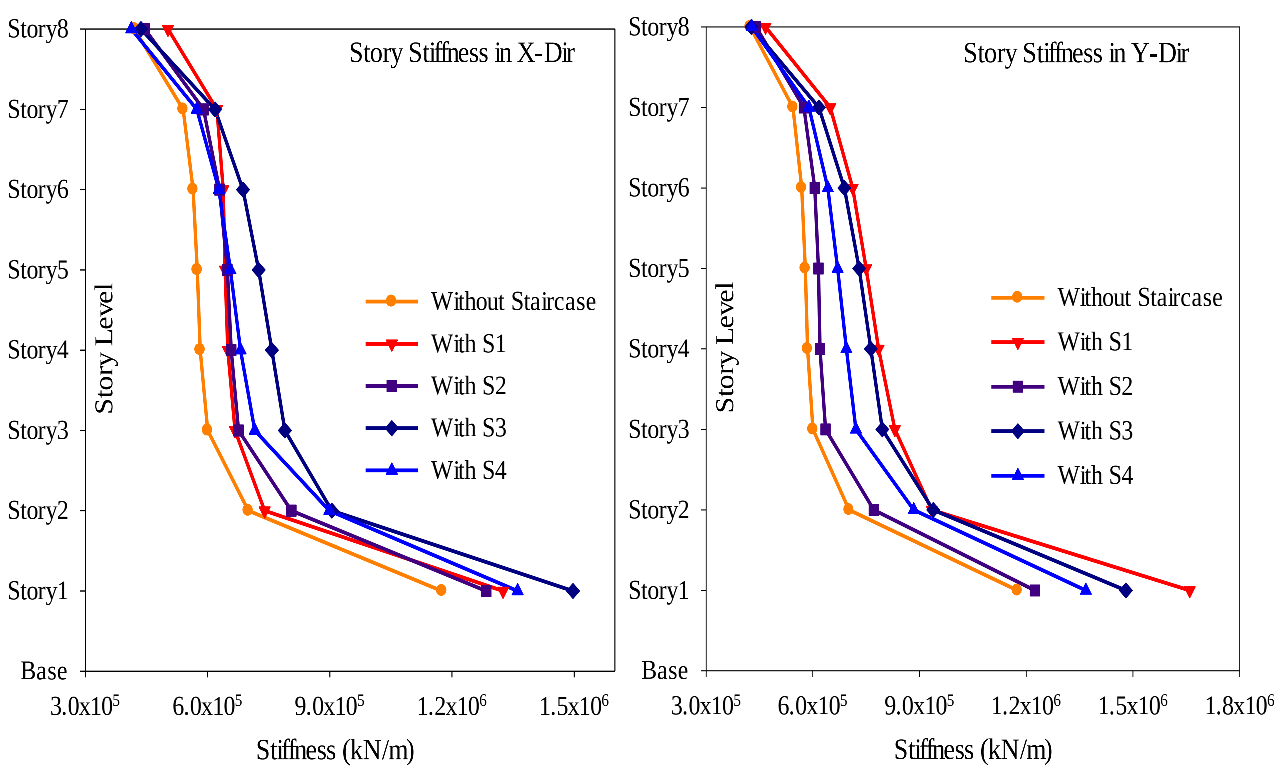


Figure 4.23: Story stiffness of irregular structures with staircase at center(G4)

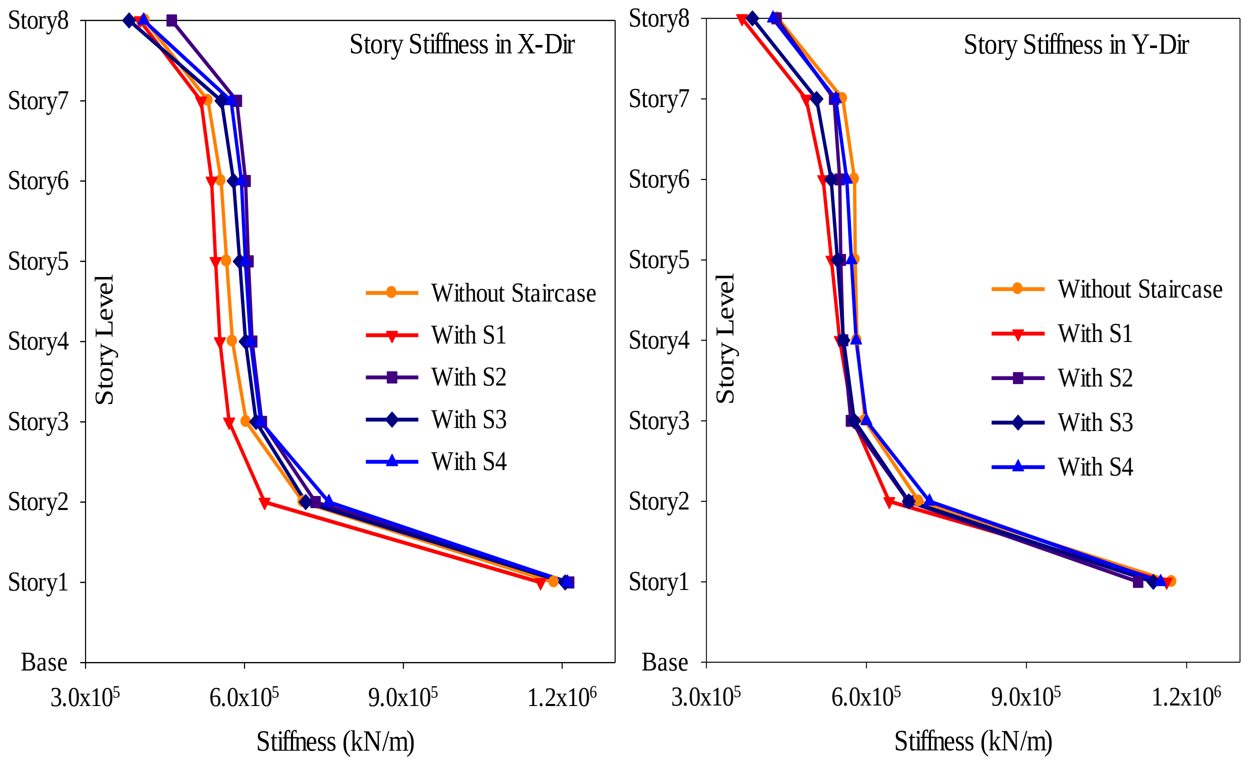


Figure 4.24: Story stiffness of irregular structures with staircase at corner(G5)

In the investigation of staircase effect on seismic response of building the reference for comparison is a building modeled without a staircase. Accordingly, stiffness of regular and irregular building modeling with a staircase at center increased whereas it is decreased on the building those modeled with a staircase at the corner of a building.

From table 4.17 and figure 4.21 to figure 4.24 staircase increase stiffness when provided at a center of a building. According to this evaluation of staircase effect on the stiffness of building structure staircase S1 and S3 has a very significant positive impact on building seismic response when provided at the center.

Regular building with S1 stair at center increase stiffness of the building structure by 18.11% and 20.36% whereas S3 increase 15.33% and 14.73% in X and Y-direction respectively which is a maximum response on G2 group modeling. In the same way on irregular building with a staircase at center S1 increase by 12.66% and 28.86% whereas S3 increase by 23.09% and 22.98% in X and Y-direction respectively as compared to building modeled without staircase.

Staircases could have either a positive or negative impact on the stiffness of buildings when provided at a corner. Also, it is very difficult to be conclusive on selecting the structurally best staircase type against seismic excitation on the irregular structure since there are several types of irregularities on building structure. Under such uncertain conditions, and particularly on plan irregular building structures considered in this research (L-shaped), it is recommended to select the staircase type that less affects the seismic response of structures. According to this investigation, the S2 staircase has less effects on the seismic response of the structure that make it preferable under the above discussed possible uncertainties.

Practically U-Shaped staircase (S4) is mostly provided on the periphery of the elevation shaft. In this research, the seismic impact of S4 without including an elevation shaft (shear wall) is considered to investigate the impact due to the stair alone. Accordingly, S4 has a considerable effect on seismic response than S2 and needs to be modeled as an integral part of building primary structural elements.

4.5.2. Eccentricity

Eccentricity is the distance between the center of rigidity and the center of mass of the building. Center of mass and stiffness mostly note coincides due to uneven distribution of building mass and stiffness irregularity of structural elements. The more eccentricity the building the higher it likely subject to torsion. Regular building structures have eccentricity very close to zero whereas the eccentricity of irregular structures is higher. Eccentricity has a significant effect on the seismic response of a building and is considered an important parameter in this investigation of staircase effects on the seismic response of reinforced concrete frame building.

Average percentage change in eccentricity due to staircase location change as compared to the offset distance is computed from the center of mass and center of rigidity result obtained from a seismic analysis of the buildings using response spectrum analysis. Accordingly, the formula.

$$\Delta e\% = \left(\frac{e_{corner} - e_{center}}{Offset\ distance}\right)100 \qquad (4.11)$$

Where:

- $\Delta_e\%$ is the percentage change in eccentricity between staircase at the corner and at the center as compared to the offset distance between the two locations.
- e_{corner} is the eccentricity of the building with a staircase at a corner
- e_{center} is the eccentricity of the building with a staircase at a corner

The offset of the corner stair for each staircase type from the same stair at the center is different in the X-direction since the plan area covered is variable for all types. Accordingly, for regular building structures with staircase type S1 and S2 is 15m, 14.25m respectively whereas for S3 and S4 is 13.5m. offset in the Y-direction to the top left corner is 13.5m for all staircase types in a regular building. Offset distance in X-direction for irregular building with S1, S2, S3, and S4 is 11.75m, 10.5m, 10.2m, and 9m respectively whereas 18m in Y-direction for all types.

Table 4.18: Average percentage change in eccentricity

Regularity condition	**Direction**	**%age change in Eccentricity With staircase compared to change in location distance**			
		With S1	**With S2**	**With S3**	**With S4**
Regular building	X-Dir	21.00%	4.51%	21.64%	11.17%
	Y-Dir	7.30%	7.80%	22.21%	11.01%
Irregular building	X-Dir	27.38%	6.23%	34.23%	14.97%
	Y-Dir	9.14%	10.78%	25.26%	14.86%

From table 4.18 above, the percentage change in eccentricity of the regular and irregular building structure with S3 is the maximum as compared to eccentricity due to other types of a staircase in both orthogonal directions. The eccentricity of a regular and irregular building in the X-direction is significantly greater than in the Y-direction on S1 because the stair maintains its rigidity in the Y-direction than in the X-direction during the relocation of the staircase. Percentage Eccentricity change in S3 is more consistent in both orthogonal directions on a regular building. The reason for it is relatively inconsistent on irregular buildings is that configuration of primary structural members causes stiffness irregularity on the building besides the contribution from the staircase affected.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

Result obtained from the evaluation of staircase effect on seismic response of RC moment resistant frame building using response spectrum analysis leads to the following conclusion.

- ❖ Staircase has significant effects on seismic performance of a building and neglecting it as an integral part of building structures in 3D modeling causes uncertainty in the analysis.
- ❖ All stairs provided at the center of regular and irregular building increased stiffness of the building subjected to seismic action by 3.48% to 28.86%. but the stiffness of a building with all stairs at the corner decreased up to 7.96% as compared to the building without a staircase.
- ❖ Lateral force resistance of straight staircase(S1) in the longitudinal direction as diagonal bracing is higher than in-plane direction. The variation is more significant on irregular buildings with stairs at center 12.66% and 28.86% in X and Y-direction respectively.
- ❖ Doglegged staircase(S2) less affects the seismic performance of a building that ranges between -3.76% to 11.21%. Also, it is stiffer in an in-plane direction than when it acts as 'K' bracing.
- ❖ L-shaped staircase (S3) responds uniformly against seismic action in the X and Y-direction and its effect on the stiffness of a building ranges from -5.82% to 23.09% as compared to a building modeled without a staircase.
- ❖ The building modeled with a U-shaped staircase(S4) at the corner generates maximum base shear relative to other types of staircase. Also, it is the 2nd less contributing to building stiffness next to a doglegged stair on the building with a staircase at the center.

Generally, staircases have positive and negative impacts on seismic response if provided at center and corner of buildings respectively. The response of irregular building with a staircase at a corner is inconsistent due to stiffness irregularity.

5.2. RECOMMENDATION

5.2.1. Recommendation for staircase utilization

To make the staircase structurally suitable for building the following recommendation shall be properly utilized during the design of RC moment resisting frame building.

- Staircase shall not be neglected in modeling 3D analysis of building especially in the high seismic region to prevent a collapse that is related to seismic action.
- Staircase has to be provided at the center of buildings or symmetrically to maximize its contribution to lateral stiffness against seismic action.
- L-shaped(S3) staircase is the best option for a building with a staircase at the center because it responds equal and the same way in both X and Y-direction directions.
- Doglegged staircase(S2) is the best option if providing a staircase at the corner is necessary to minimize the seismic response contribution of the stair.
- Since the straight flight staircase(S1) is orientation sensitive in response against the lateral force the longitudinal direction should be placed in the direction in which the building requires bracing to maximize its utilization.

5.2.2. Recommendation for future studies

- Future study shall make a further study on the seismic effect of other types of staircase remain uncovered in this research such as stair with spiral shapes.
- Since this research is limited to plan irregular buildings with L-shape, future research is recommended to cover other buildings with different irregularities.
- Despite the width of a staircase that could possibly affect the seismic response behavior of the staircase it is taken as constant (1.5m) in all cases for this research. It is recommended to extend related research that includes variable stair width.
- Since many researches focuses on Staircase effects on moment resisting frame building, it is recommended to extend the scope to other structural system specially which includes shear walls.

REFERENCES

- Aghajani-delavar, M. and Varnosfaderani, M. P. (2017) ‘Effects of staircase on the seismic performance of reinforced concrete frame buildings considering the position of the staircase’, (August).
- Ahirwal, A. et al. (2008) ‘Effects of Staircase on the Seismic Behavior of Rc Moment Frame Buildings’, AIP Conference Proceedings, 11(4), pp. 105–122. doi: 10.21307/acee-2018-058.
- Arya V Manmathan and Aiswarya S (2017) ‘Analysis of Buildings with Varying Percentages of Diaphragm Openings’, International Journal of Engineering Research and, V6(06), pp. 461–466. doi: 10.17577/ijertv6is060254.
- Čada, P. and Máca, J. (2017) ‘Comparison of Methods Used for Seismic Analysis of Structures’, Acta Polytechnica CTU Proceedings, 13, p. 20. doi: 10.14311/app.2017.13.0020.
- Cao, Z., Bian, C. and Xu, C. (2014) ‘Analysis of the Interaction between Stair and Frame under Horizontal Earthquake Action Based on ETABS’, in International Conference on Mechanics and Civil Engineering (ICMCE 2014) Analysis. Shenyang, China, pp. 478–483.
- Cosenza, E., Verderame, G. M. and Zambrano, A. (2008) ‘Seismic Performance of Stairs in The Existing Reinforced Concrete Building’, in World Conference on Earthquake Engineering. Beijing, China.
- Danish, M. et al. (2013) ‘Effect of Staircase on Rc Frame’, in Trends and Challenges in Concrete Structures. Ghaziabad, UP, India.
- Deshmukh, P. and Banarase, M. A. (2017) ‘Effects of Staircase on The Seismic Performance of RCC’, International Journal of Advance Engineering and Research Development, 4(4), pp. 1000–1018.
- Elnashai, A. S. (2008) Fundamentals of Earthquake. USA: Wiley.

- Ethiopia Ministry of Construction (2015) ES EN- 8 Part 1 Design of Structures for Earthquake Resistance. Addis Abeba, Ethiopia.

- Freweyni Mekonen (2016) The Role of Soil Amplification Studies in Seismic Hazard Assessment in Some Selected Parts of Adama Town, Central Ethiopia. Addis Ababa University.

- Getachew, K., Chen, D. and Peng, G. (2020) 'Seismic Performance Evaluation of RC Frame Designed Using Ethiopian and Chinese Seismic Codes', Advances in Civil Engineering, 2020, p. 24.

- Ghodke and U.R.Awari (2016) 'Torsional Effect for Unsymmetrical R.C. Frames', International Research Journal of Engineering and Technology (IRJET), 03(07), pp. 812–818.

- Karam, G. and Tabbara, M. (2009) 'Properties of pre-cast terrazzo tiles and recommended specifications', Cerâmica, 55, pp. 84–87.

- Khadse, P. and Khedikar, P. A. (2018) 'Seismic Analysis of High Rise R . C Frame Structure with Staircase at Different Location', International Journal of Engineering and Science (IJES), pp. 5–20.

- Kolekar, D. M. and Pawar, M. M. (2017) 'Study of Base Shear , Storey Shear and Base Moment on Multistory Building for Different Seismic Zones', International Journal of Engineering Science and Computing, 7(6), pp. 13526–13530.

- Patil Jaya, P. and Alandkar, D. P. M. (2016) 'International journal of engineering sciences & research technology drift analysis in multistoried building', International Journal of Engineering Sciences & Research Technology, 5(12), pp. 490–505.

- Qiwang, S. (2010) 'Finite Element Analysis of Staircase under Earthquake Action', Advanced Materials Research, 163–167, pp. 2964–2968. doi: 10.4028/www.scientific.net/AMR.163-167.2964.

- Ramakrishna, J. and Riyaz, S. (2017) 'An Experimental Study on Seismic Analysis of Multy Storey Building Using Equivalent Static Method', Journal of Emerging

Technologies and Innovative Research (JETIR), 4(11), pp. 734–741.

- Ramin Taghinezhad, Arash Taghinezhad, Vahid Mahdavifar, V. S. (2018) 'Evaluation of Story Drift under Pushover Analysis in Reinforced Concrete Moment Frames', International Journal of Research and Engineering, 5(1), pp. 296–302. Available at: http://digital.ijre.org/index.php/int_j_res_eng/article/view/323.

- Shelotkar, A. R. (2016) 'Effect Of Staircase On Seismic Performance Of Multistoried Frame Structure', International Journal of Innovative and Emerging Research in Engineering, 3(1), pp. 301–307.

- Shyamananda Singh, C. . (2012) 'Effects of Staircase on The Seismic Performance of RCC Frame Building.', International Journal of Engineering Science and Technology (IJEST) EFFECTS, 4(04), pp. 1336–1350.

- Spectra, R. (2002) 'Chapter 4 Response Spectrum Method', Response Spectrum Method 4.1, pp. 102–153.

- Titiksh, A. and M K, G. (2015) 'A Study of the Various Structural Framing Systems Subjected to Seismic Loads', International Journal of Civil Engineering, 2(4), pp. 21–28. doi: 10.14445/23488352/ijce-v2i4p105.

APPENDIX A

Story Displacement

Table A1: Story displacement of buildings without staircase (G1)

Story	Elevation (m)	Regular at center		Regular at corner		Irregular at center		Irregular at corner	
		X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)
Story8	24	17.602	17.593	17.967	17.983	18.665	18.659	17.893	19.172
Story7	21	16.873	16.865	17.224	17.240	17.834	17.829	17.095	18.320
Story6	18	15.558	15.551	15.882	15.897	16.397	16.392	15.721	16.845
Story5	15	13.642	13.636	13.927	13.940	14.333	14.328	13.749	14.726
Story4	12	11.190	11.185	11.425	11.435	11.709	11.705	11.238	12.031
Story3	9	8.288	8.284	8.462	8.470	8.622	8.619	8.282	8.861
Story2	6	5.074	5.071	5.181	5.186	5.231	5.230	5.035	5.378
Story1	3	1.897	1.896	1.937	1.939	1.925	1.924	1.863	1.980
Base	0	0	0	0	0	0	0	0	0

Table A2: Story displacement of regular building with staircase at center(G2)

Story	Elevation (m)	With staircase							
		With S1		With S2		With S3		With S4	
		X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)
Story8	24	16.561	16.403	17.004	17.315	16.288	16.230	17.208	16.777
Story7	21	15.797	15.628	16.270	16.600	15.474	15.432	16.455	16.036
Story6	18	14.483	14.311	14.972	15.309	14.136	14.104	15.133	14.742
Story5	15	12.635	12.471	13.109	13.428	12.294	12.272	13.242	12.895
Story4	12	10.322	10.176	10.747	11.021	10.018	10.006	10.848	10.564
Story3	9	7.630	7.511	7.970	8.172	7.392	7.392	8.038	7.830
Story2	6	4.678	4.596	4.904	5.015	4.536	4.549	4.940	4.817
Story1	3	1.761	1.723	1.856	1.884	1.719	1.739	1.866	1.824
Base	0	0	0	0	0	0	0	0	0

Table A2: Story drift of regular building with staircase at corner(G3)

Story	Elevation (m)	With staircase							
		With S1		With S2		With S3		With S4	
		X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)
Story8	24	21.515	24.715	21.219	19.976	23.511	23.492	21.842	22.152
Story7	21	20.599	23.701	20.344	19.149	22.533	22.508	20.930	21.218
Story6	18	18.970	21.857	18.762	17.656	20.772	20.741	19.290	19.548
Story5	15	16.618	19.167	16.455	15.480	18.210	18.175	16.907	17.127
Story4	12	13.621	15.721	13.499	12.694	14.935	14.899	13.862	14.038
Story3	9	10.085	11.641	9.998	9.397	11.063	11.028	10.263	10.391
Story2	6	6.180	7.122	6.120	5.747	6.777	6.745	6.282	6.360
Story1	3	2.321	2.659	2.287	2.145	2.539	2.516	2.350	2.378
Base	0	0	0	0	0	0	0	0	0

Table A3: Story displacement of irregular building with staircase at center(G4)

Story	Elevation (m)	With staircase							
		With S1		With S2		With S3		With S4	
		X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)
Story8	24	17.780	16.428	17.706	18.364	15.894	15.851	17.145	17.326
Story7	21	16.973	15.493	16.895	17.548	15.068	15.039	16.330	16.505
Story6	18	15.585	14.033	15.511	16.136	13.735	13.715	14.964	15.127
Story5	15	13.606	12.095	13.546	14.108	11.922	11.908	13.045	13.189
Story4	12	11.102	9.757	11.066	11.533	9.695	9.688	10.643	10.762
Story3	9	8.166	7.115	8.164	8.505	7.139	7.142	7.846	7.934
Story2	6	4.947	4.298	4.981	5.176	4.374	4.388	4.789	4.841
Story1	3	1.813	1.585	1.857	1.917	1.656	1.678	1.789	1.806
Base	0	0	0	0	0	0	0	0	0

Table A5: Story displacement of irregular building with staircase at corner(G5)

Story	Elevation (m)	With staircase							
		With S1		With S2		With S3		With S4	
		X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)	X-Dir (mm)	Y-Dir (mm)
Story8	24	21.991	27.397	21.318	21.914	21.471	25.422	21.274	23.780
Story7	21	20.916	26.176	20.428	20.939	20.561	24.241	20.374	22.684
Story6	18	19.141	24.056	18.829	19.250	18.939	22.240	18.767	20.818
Story5	15	16.649	21.018	16.502	16.825	16.588	19.406	16.437	18.170
Story4	12	13.526	17.163	13.523	13.745	13.588	15.833	13.463	14.830
Story3	9	9.888	12.634	9.999	10.124	10.046	11.654	9.951	10.922
Story2	6	5.918	7.660	6.105	6.147	6.136	7.076	6.075	6.641
Story1	3	2.166	2.811	2.271	2.264	2.287	2.606	2.261	2.456
Base	0	0	0	0	0	0	0	0	0

APPENDIX B

Story Shear

Table B1: Story shear of regular and irregular building without staircase at center and corner(G1)

Story	Elevation (m)	Regular at center		Regular at corner		Irregular at center		Irregular at corner	
		X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)
Story8	24	580.4	580.4	580.1	580.2	403.4	403.5	403.0	403.2
Story7	21	1208.6	1208.7	1208.0	1208.1	842.8	843.0	842.6	841.8
Story6	18	1715.9	1716.1	1715.0	1715.1	1197.4	1197.7	1197.4	1195.8
Story5	15	2133.2	2133.5	2132.0	2132.2	1489.7	1490.1	1489.8	1487.4
Story4	12	2485.6	2486.0	2484.2	2484.5	1736.2	1736.6	1736.5	1733.5
Story3	9	2782.0	2782.3	2780.4	2780.7	1942.3	1942.8	1942.7	1939.3
Story2	6	3006.6	3007.1	3005.0	3005.3	2097.6	2098.2	2098.0	2094.5
Story1	3	3122.9	3123.3	3121.2	3121.5	2176.6	2177.2	2176.8	2173.4
Base	0	3122.9	3123.3	3121.2	3121.5	2176.6	2177.2	2176.8	2173.4

Table B2: Story shear of regular structure with staircase at center(G2)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)
Story8	24	620.8	627.2	600.3	587.6	600.7	600.2	606.5	607.7
Story7	21	1306.9	1321.9	1266.0	1234.0	1269.7	1268.8	1280.9	1283.9
Story6	18	1863.9	1886.8	1806.6	1757.8	1811.3	1810.6	1829.0	1833.6
Story5	15	2322.4	2351.9	2252.2	2189.6	2256.1	2255.7	2280.9	2286.8
Story4	12	2707.7	2742.5	2627.6	2553.8	2629.3	2629.1	2661.3	2668.2
Story3	9	3028.5	3066.6	2941.2	2859.2	2939.6	2939.5	2978.5	2986.3
Story2	6	3268.7	3308.2	3177.5	3090.0	3172.3	3172.3	3216.9	3225.3
Story1	3	3390.9	3430.2	3299.3	3209.4	3291.4	3292.1	3339.4	3348.0
Base	0	3390.9	3430.2	3299.3	3209.4	3291.4	3292.1	3339.4	3348.0

Table B3: Story shear of regular structure with staircase at corner(G3)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)
Story8	24	591.3	598.1	594.1	585.9	594.5	594.9	588.2	607.8
Story7	21	1235.9	1269.2	1247.1	1228.6	1260.2	1259.7	1237.4	1278.6
Story6	18	1757.8	1809.6	1775.9	1748.7	1797.1	1795.8	1763.1	1822.0
Story5	15	2187.6	2251.9	2210.9	2176.8	2237.2	2235.1	2195.3	2268.9
Story4	12	2550.0	2623.2	2577.7	2538.1	2607.9	2605.3	2559.3	2645.3
Story3	9	2853.5	2932.5	2885.3	2841.3	2917.7	2915.1	2864.2	2960.4
Story2	6	3081.9	3164.0	3117.7	3070.8	3150.8	3149.3	3094.3	3198.3
Story1	3	3198.7	3284.6	3238.2	3189.8	3272.9	3273.0	3213.4	3321.5
Base	0	3198.7	3284.6	3238.2	3189.8	3272.9	3273.0	3213.4	3321.5

Table B4: Story shear of irregular structure with staircase at center(G4)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)
Story8	24	423.2	465.6	418.7	411.4	422.7	422.7	428.0	435.3
Story7	21	891.0	987.6	888.3	869.7	901.1	901.1	912.9	927.5
Story6	18	1271.3	1409.4	1270.1	1241.3	1289.2	1289.5	1308.5	1329.0
Story5	15	1585.6	1755.0	1585.5	1548.2	1608.1	1608.9	1635.4	1660.8
Story4	12	1849.9	2042.9	1850.7	1806.7	1874.7	1875.7	1909.8	1939.4
Story3	9	2068.8	2278.7	2071.0	2022.1	2094.3	2095.5	2136.6	2169.8
Story2	6	2231.2	2451.1	2235.9	2183.7	2257.2	2258.6	2305.2	2341.2
Story1	3	2311.9	2534.9	2319.6	2265.8	2338.8	2340.9	2389.9	2427.6
Base	0	2311.9	2534.9	2319.6	2265.8	2338.8	2340.9	2389.9	2427.6

Table B5: Story Shear of irregular structure with staircase at corner(G5)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)	X-Dir (kN)	Y-Dir (kN)
Story8	24	410.9	424.4	414.2	407.0	404.0	420.7	405.2	430.1
Story7	21	864.2	906.4	877.0	858.7	862.4	894.9	861.4	911.9
Story6	18	1231.4	1293.6	1252.6	1224.2	1235.3	1278.6	1231.7	1302.7
Story5	15	1534.4	1609.8	1562.3	1525.7	1540.8	1592.7	1536.9	1624.5
Story4	12	1789.4	1874.0	1822.9	1779.6	1796.9	1856.3	1793.4	1894.8
Story3	9	2001.5	2092.1	2040.0	1991.5	2009.1	2075.4	2006.6	2119.4
Story2	6	2159.7	2253.7	2202.8	2151.0	2168.5	2240.6	2166.1	2287.4
Story1	3	2239.0	2336.3	2285.5	2232.3	2250.7	2326.5	2247.3	2372.8
Base	0	2239.0	2336.3	2285.5	2232.3	2250.7	2326.5	2247.3	2372.8

APPENDIX C

Base overturning moment

Table C1: Base overturning moment of regular and irregular building without staircase at center and corner(G1)

Story	Elevation (m)	Regular at center		Regular at corner		irregular at center		irregular at corner	
		X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)
Base	0	48996.0	48989.2	48966.7	48961.2	34229.1	34219.8	34166.3	34228.2

Table C2: Base overturning moment of regular building with staircase at center (G2)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)
Base	0	54114.4	53422.6	50369.6	51854.9	51919.1	51919.0	52665.9	52526.0

Table C3: Base overturning moment of regular building with staircase at corner (G3)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)
Base	0	51749.0	50262.6	50053.0	50844.0	51392.9	51442.1	52189.2	50490.7

Table C4: Base overturning moment of irregular building with staircase at center (G4)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)
Base	0	40340.4	36468.8	35646.0	36533.5	37066.6	37042.3	38303.2	37720.1

Table C5: Base overturning moment of irregular building with staircase at corner (G5)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)	X-Dir (kN-m)	Y-Dir (kN-m)
Base	0	36984.2	35276.8	35107.0	35970.8	36633.1	35460.1	37404.3	35395.8

APPENDIX D

Story Stiffness

Table D1: Story stiffness of regular and irregular building without staircase at center and corner(G1)

Story	Elevation (m)	Regular at center		Regular at corner		Irregular at center		Irregular at corner	
		X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)
Story8	24	617276	617341	618332	618868	420155	424046	412453	434142
Story7	21	775697	775762	780472	780119	540094	544447	531416	555792
Story6	18	804447	804503	811403	811014	564533	568821	556026	577850
Story5	15	815013	815065	823285	822888	574555	578730	566256	578919
Story4	12	826776	826824	836111	835701	581846	585348	577350	582424
Story3	9	858362	858396	859408	859631	600417	600518	603536	597423
Story2	6	994645	995086	1000780	999471	700088	701982	710859	698224
Story1	3	1647566	1647815	1648857	1649974	1174959	1175124	1184947	1172343
Base	0	0	0	0	0	0	0	0	0

Table D2: Story stiffness of regular building with staircase at center (G2)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)
Story8	24	736888	736774	622403	609475	621913	596212	580842	597271
Story7	21	920155	930233	818337	786601	842674	829783	793162	805596
Story6	18	956276	972195	869645	826695	918547	909488	863511	870231
Story5	15	973665	993216	894273	843481	960134	953275	900123	903437
Story4	12	991151	1013676	917001	860042	997513	991601	932102	932734
Story3	9	1021245	1046754	958386	897780	1042247	1046427	982773	986313
Story2	6	1120303	1150073	1142791	1089599	1203875	1247434	1211975	1209220
Story1	3	1928043	1991215	1787747	1703793	1947035	1929372	1832604	1839517
Base	0	0	0	0	0	0	0	0	0

Table D3: Story stiffness of regular building with staircase at corner (G3)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)
Story8	24	627909	582012	677068	624574	583262	559346	593355	609873
Story7	21	767163	746732	832758	805692	758348	759635	802202	807742
Story6	18	781951	786621	847371	824743	783281	784447	820631	828258
Story5	15	784754	805195	850689	824137	794347	795752	826420	834769
Story4	12	790283	825245	857204	827591	806539	807789	834826	843572
Story3	9	809229	859649	878021	846401	831502	831907	856898	866975
Story2	6	889489	951785	1010211	1002454	955462	970816	1032276	1033330
Story1	3	1551956	1684781	1661778	1607248	1586098	1599097	1621104	1631755
Base	0	0	0	0	0	0	0	0	0

Table D4: Story stiffness of irregular building with staircase at center (G4)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)
Story8	24	502688	466923	445811	440208	436338	427227	412619	428674
Story7	21	623097	649123	590211	575064	618432	617320	573766	589092
Story6	18	638228	712179	629329	605687	686777	688698	627856	642028
Story5	15	642946	750017	648438	615950	725485	730033	655966	670032
Story4	12	649583	784983	657879	620249	757715	762811	680995	694509
Story3	9	667521	830775	676018	635772	789871	795453	716066	721136
Story2	6	740147	934144	805492	771702	904884	938666	899065	883910
Story1	3	1325161	1659404	1283841	1224646	1497169	1480377	1361171	1367604
Base	0	0	0	0	0	0	0	0	0

Table D5: Story stiffness of irregular building with staircase at corner (G5)

Story	Elevation (m)	With S1		With S2		With S3		With S4	
		X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)	X-Dir (kN/m)	Y-Dir (kN/m)
Story8	24	402491	366897	462800	431679	382107	386406	409512	425049
Story7	21	518111	487029	585595	539466	556646	506517	574834	542537
Story6	18	538071	518983	601855	549958	579440	533768	594097	563342
Story5	15	545573	534400	607367	552008	590981	545754	601803	571798
Story4	12	553568	550055	614476	556320	601940	557047	611422	580882
Story3	9	571025	575549	632666	570888	621932	577201	630602	600014
Story2	6	637800	642995	734119	678480	715570	679458	759427	718105
Story1	3	1159078	1162763	1213006	1109206	1205487	1137835	1209746	1151624
Base	0	0	0	0	0	0	0	0	0

APPENDIX E

Center of Mass and Center of Stiffness

Center of mass

Table E1: Center of mass of buildings without staircase (G1)

Story	Elevation	Regular at center		Regular at corner		Irregular at center		Irregular at corner	
		XCCM	YCCM	XCCM	YCCM	XCCM	YCCM	XCCM	YCCM
	m	m	m	m	m	m	m	m	m
Story8	24	15.751	15.747	15.855	15.644	12.524	12.520	12.641	12.332
Story7	21	15.751	15.747	15.845	15.653	12.524	12.521	12.631	12.350
Story6	18	15.751	15.747	15.842	15.655	12.524	12.521	12.629	12.355
Story5	15	15.751	15.747	15.841	15.656	12.525	12.521	12.628	12.357
Story4	12	15.751	15.747	15.840	15.657	12.525	12.521	12.627	12.358
Story3	9	15.751	15.747	15.840	15.657	12.525	12.521	12.626	12.359
Story2	6	15.751	15.747	15.840	15.657	12.525	12.521	12.626	12.359
Story1	3	15.751	15.747	15.839	15.658	12.525	12.521	12.625	12.361
Base	0	0	0	0	0	0	0	0	0

Table E2: Center of mass for regular building with staircase at center (G2)

Story	Elevation	With S1		With S2		With S3		With S4	
		XCCM	YCCM	XCCM	YCCM	XCCM	YCCM	XCCM	YCCM
	m	m	m	m	m	m	m	m	m
Story8	24	15.750	15.739	15.748	15.744	15.759	15.751	15.754	15.745
Story7	21	15.750	15.745	15.749	15.743	15.755	15.748	15.752	15.745
Story6	18	15.750	15.747	15.749	15.743	15.754	15.747	15.751	15.745
Story5	15	15.750	15.748	15.750	15.742	15.754	15.746	15.751	15.745
Story4	12	15.750	15.748	15.750	15.742	15.754	15.746	15.751	15.745
Story3	9	15.750	15.749	15.750	15.742	15.754	15.746	15.751	15.745
Story2	6	15.750	15.749	15.750	15.742	15.753	15.746	15.750	15.745
Story1	3	15.750	15.749	15.750	15.742	15.753	15.746	15.750	15.745
Base	0	-	-	-	-	-	-	-	-

Table E3: Center of mass for regular building with staircase at center (G3)

Story	Elevation	With S1		With S2		With S3		With S4	
		XCCM	YCCM	XCCM	YCCM	XCCM	YCCM	XCCM	YCCM
	m	m	m	m	m	m	m	m	m
Story8	24	15.786	15.703	15.889	15.613	15.852	15.658	15.894	15.602
Story7	21	15.787	15.707	15.879	15.621	15.831	15.672	15.883	15.611
Story6	18	15.788	15.708	15.876	15.623	15.826	15.676	15.881	15.614
Story5	15	15.788	15.708	15.875	15.624	15.823	15.677	15.879	15.615
Story4	12	15.788	15.709	15.874	15.624	15.822	15.678	15.879	15.616
Story3	9	15.788	15.709	15.874	15.625	15.821	15.679	15.878	15.616
Story2	6	15.788	15.709	15.873	15.625	15.820	15.679	15.878	15.616
Story1	3	15.788	15.709	15.873	15.625	15.818	15.682	15.877	15.617
Base	0	-	-	-	-	-	-	-	-

Table E4: Center of mass for irregular building with staircase at center (G4)

Story	Elevation	With S1		With S2		With S3		With S4	
		XCCM	YCCM	XCCM	YCCM	XCCM	YCCM	XCCM	YCCM
	m	m	m	m	m	m	m	m	m
Story8	24	15.786	15.703	15.889	15.613	15.852	15.658	15.894	15.602
Story7	21	15.787	15.707	15.879	15.621	15.831	15.672	15.883	15.611
Story6	18	15.788	15.708	15.876	15.623	15.826	15.676	15.881	15.614
Story5	15	15.788	15.708	15.875	15.624	15.823	15.677	15.879	15.615
Story4	12	15.788	15.709	15.874	15.624	15.822	15.678	15.879	15.616
Story3	9	15.788	15.709	15.874	15.625	15.821	15.679	15.878	15.616
Story2	6	15.788	15.709	15.873	15.625	15.820	15.679	15.878	15.616
Story1	3	15.788	15.709	15.873	15.625	15.818	15.682	15.877	15.617
Base	0	-	-	-	-	-	-	-	-

Table E5: Center of mass for irregular building with staircase at corner (G5)

Story	Elevation	With S1		With S2		With S3		With S4	
		XCCM	YCCM	XCCM	YCCM	XCCM	YCCM	XCCM	YCCM
	m	m	m	m	m	m	m	m	m
Story8	24	12.563	12.440	12.680	12.276	12.638	12.356	12.685	12.256
Story7	21	12.565	12.448	12.670	12.292	12.616	12.384	12.674	12.276
Story6	18	12.566	12.450	12.667	12.297	12.611	12.392	12.671	12.281
Story5	15	12.567	12.451	12.666	12.299	12.608	12.395	12.670	12.283
Story4	12	12.567	12.451	12.665	12.300	12.607	12.397	12.669	12.284
Story3	9	12.567	12.452	12.665	12.300	12.606	12.398	12.669	12.285
Story2	6	12.567	12.452	12.664	12.301	12.605	12.399	12.668	12.286
Story1	3	12.567	12.452	12.664	12.302	12.602	12.404	12.668	12.286
Base	0	-	-	-	-	-	-	-	-

Center of rigidity

Table E6: Center of building without staircase at center and corner(G1)

Story	Elevation	Regular at center		Regular at corner		irregular at center		irregular at corner	
		XCR	YCR	XCR	YCR	XCR	YCR	XCR	YCR
	m	m	m	m	m	m	m	m	m
Story8	24	15.750	15.749	15.784	15.713	12.264	12.265	12.300	12.198
Story7	21	15.750	15.749	15.784	15.714	12.295	12.296	12.330	12.230
Story6	18	15.750	15.749	15.784	15.714	12.321	12.321	12.356	12.257
Story5	15	15.750	15.749	15.783	15.714	12.348	12.348	12.382	12.285
Story4	12	15.750	15.749	15.782	15.715	12.379	12.379	12.413	12.318
Story3	9	15.750	15.749	15.780	15.718	12.421	12.421	12.452	12.364
Story2	6	15.750	15.750	15.776	15.722	12.487	12.488	12.514	12.439
Story1	3	15.750	15.750	15.772	15.728	12.616	12.616	12.640	12.580
Base	0	0	0	0	0	0	0	0	0

Table E7: Center of rigidity for regular building with staircase at center (G2)

Story	Elevation	With S1		With S2		With S3		With S4	
		XCR	YCR	XCR	YCR	XCR	YCR	XCR	YCR
	m	m	m	m	m	m	m	m	m
Story8	24	15.750	15.742	15.749	15.780	15.598	15.902	15.750	15.900
Story7	21	15.750	15.742	15.750	15.781	15.583	15.916	15.750	15.904
Story6	18	15.750	15.741	15.749	15.782	15.568	15.932	15.750	15.908
Story5	15	15.750	15.740	15.749	15.782	15.556	15.945	15.750	15.910
Story4	12	15.750	15.739	15.749	15.782	15.548	15.953	15.751	15.909
Story3	9	15.750	15.736	15.749	15.781	15.549	15.954	15.751	15.903
Story2	6	15.750	15.729	15.749	15.778	15.567	15.940	15.753	15.887
Story1	3	15.750	15.720	15.748	15.773	15.623	15.896	15.758	15.853
Base	0	0	0	0	0	0	0	0	0

Table E8: Center of rigidity for regular building with staircase at corner (G3)

Story	Elevation	With S1		With S2		With S3		With S4	
		XCR	YCR	XCR	YCR	XCR	YCR	XCR	YCR
	m	m	m	m	m	m	m	m	m
Story8	24	13.742	16.400	15.212	16.674	13.353	18.145	14.488	17.126
Story7	21	13.402	16.462	15.192	16.730	13.040	18.462	14.391	17.224
Story6	18	13.012	16.520	15.176	16.785	12.701	18.809	14.297	17.323
Story5	15	12.659	16.576	15.168	16.823	12.412	19.105	14.226	17.397
Story4	12	12.348	16.639	15.173	16.833	12.208	19.326	14.194	17.431
Story3	9	12.097	16.720	15.203	16.796	12.160	19.408	14.228	17.400
Story2	6	11.936	16.877	15.281	16.671	12.452	19.196	14.386	17.246
Story1	3	11.908	17.266	15.463	16.387	13.470	18.399	14.785	16.864
Base	0	0	0	0	0	0	0	0	0

Table E9: Center of rigidity for irregular building with staircase at center (G4)

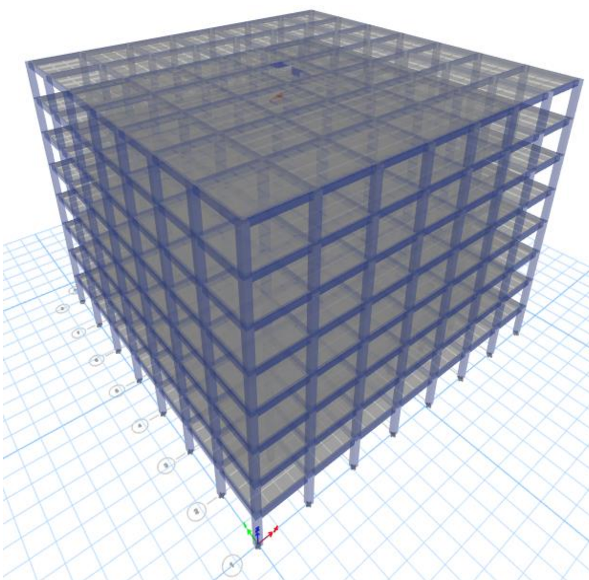
Story	Elevation	With S1		With S2		With S3		With S4	
		XCR	YCR	XCR	YCR	XCR	YCR	XCR	YCR
	m	m	m	m	m	m	m	m	m
Story8	24	12.312	12.152	12.254	12.190	12.194	12.198	12.110	12.314
Story7	21	12.340	12.177	12.282	12.214	12.210	12.213	12.130	12.340
Story6	18	12.363	12.197	12.305	12.233	12.220	12.223	12.145	12.360
Story5	15	12.386	12.218	12.330	12.255	12.233	12.236	12.164	12.381
Story4	12	12.408	12.243	12.359	12.283	12.251	12.253	12.191	12.406
Story3	9	12.431	12.279	12.400	12.325	12.280	12.282	12.235	12.440
Story2	6	12.459	12.335	12.466	12.402	12.340	12.340	12.317	12.496
Story1	3	12.509	12.449	12.598	12.564	12.484	12.479	12.493	12.615
Base	0	0	0	0	0	0	0	0	0

Table E10: Center of rigidity for irregular building with staircase at corner (G5)

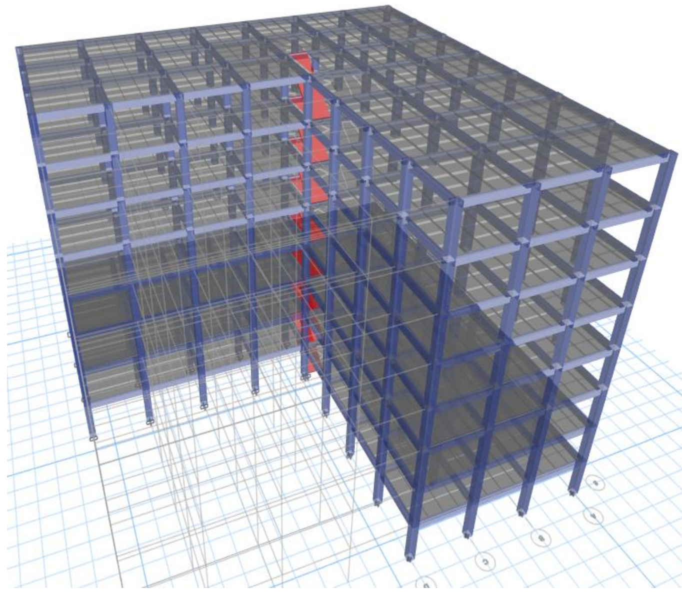
Story	Elevation	With S1		With S2		With S3		With S4	
		XCR	YCR	XCR	YCR	XCR	YCR	XCR	YCR
	m	m	m	m	m	m	m	m	m
Story8	24	10.224	13.383	11.708	13.854	9.449	15.714	10.995	14.559
Story7	21	9.921	13.496	11.717	13.970	9.135	16.133	10.930	14.738
Story6	18	9.570	13.596	11.726	14.079	8.790	16.582	10.866	14.911
Story5	15	9.253	13.692	11.744	14.162	8.500	16.975	10.826	15.048
Story4	12	8.974	13.793	11.782	14.204	8.302	17.276	10.827	15.126
Story3	9	8.750	13.915	11.858	14.178	8.280	17.410	10.902	15.107
Story2	6	8.600	14.132	12.012	14.032	8.657	17.190	11.124	14.911
Story1	3	8.524	14.675	12.346	13.692	9.927	16.271	11.655	14.406
Base	0	0	0	0	0	0	0	0	0

APPENDIX F

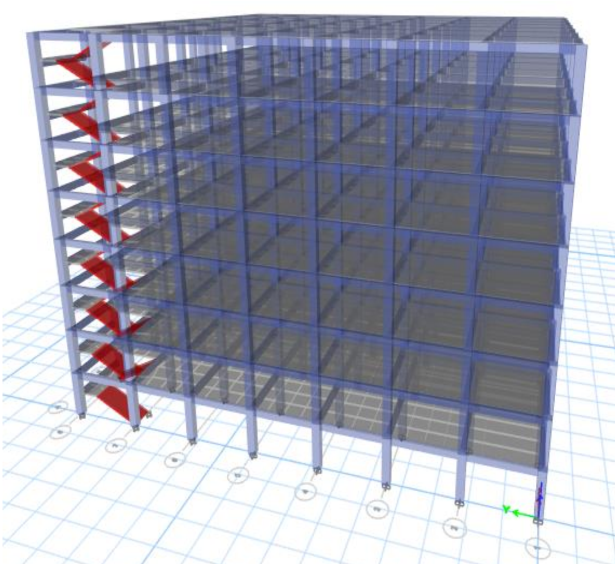
SELECTED FIGURES



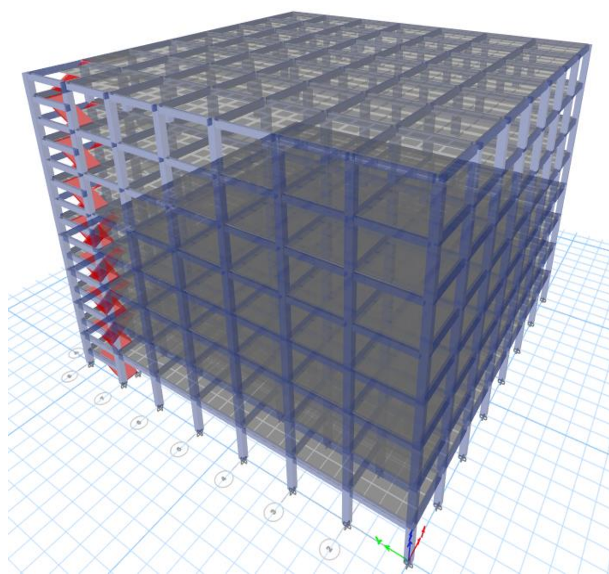
a) Regular building with staircase at center



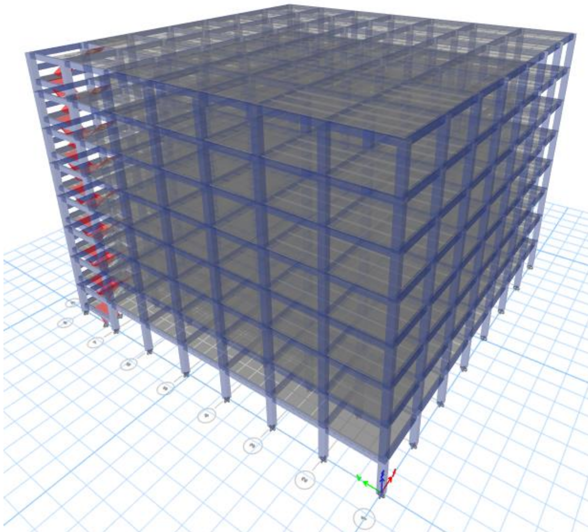
b) Irregular building with staircase at center



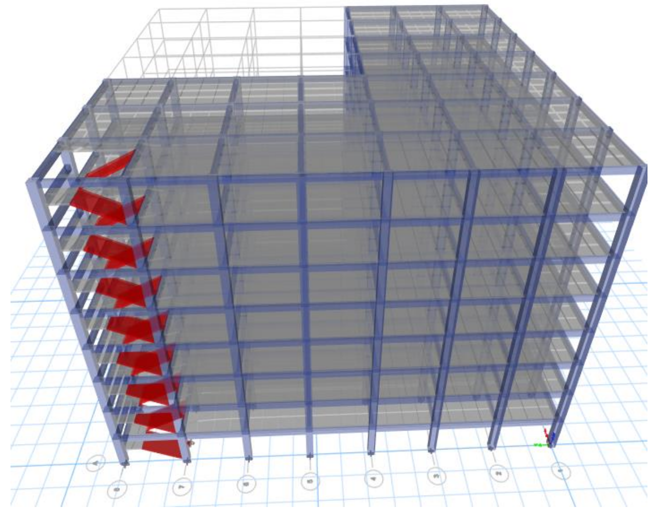
c) Regular building with S2 staircase at corner



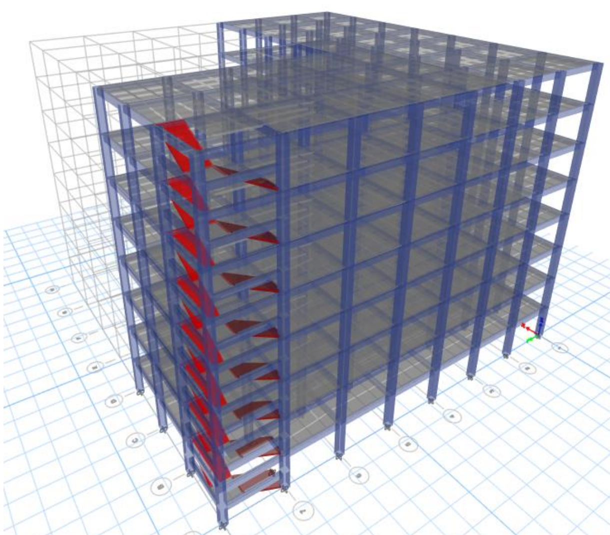
d) Regular building with S3 staircase at corner



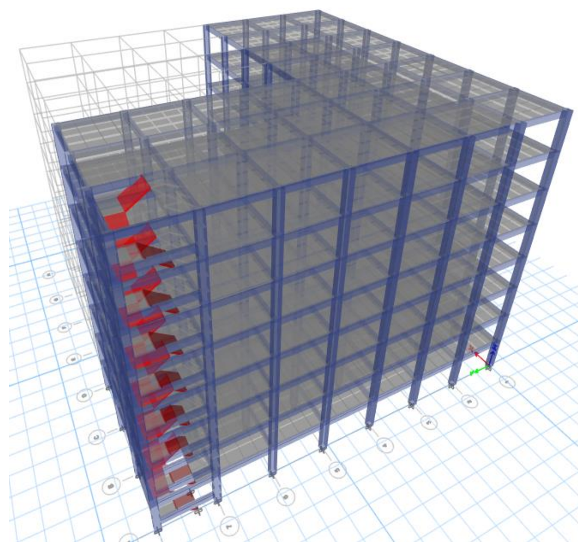
e) Regular building with S4 staircase at corner



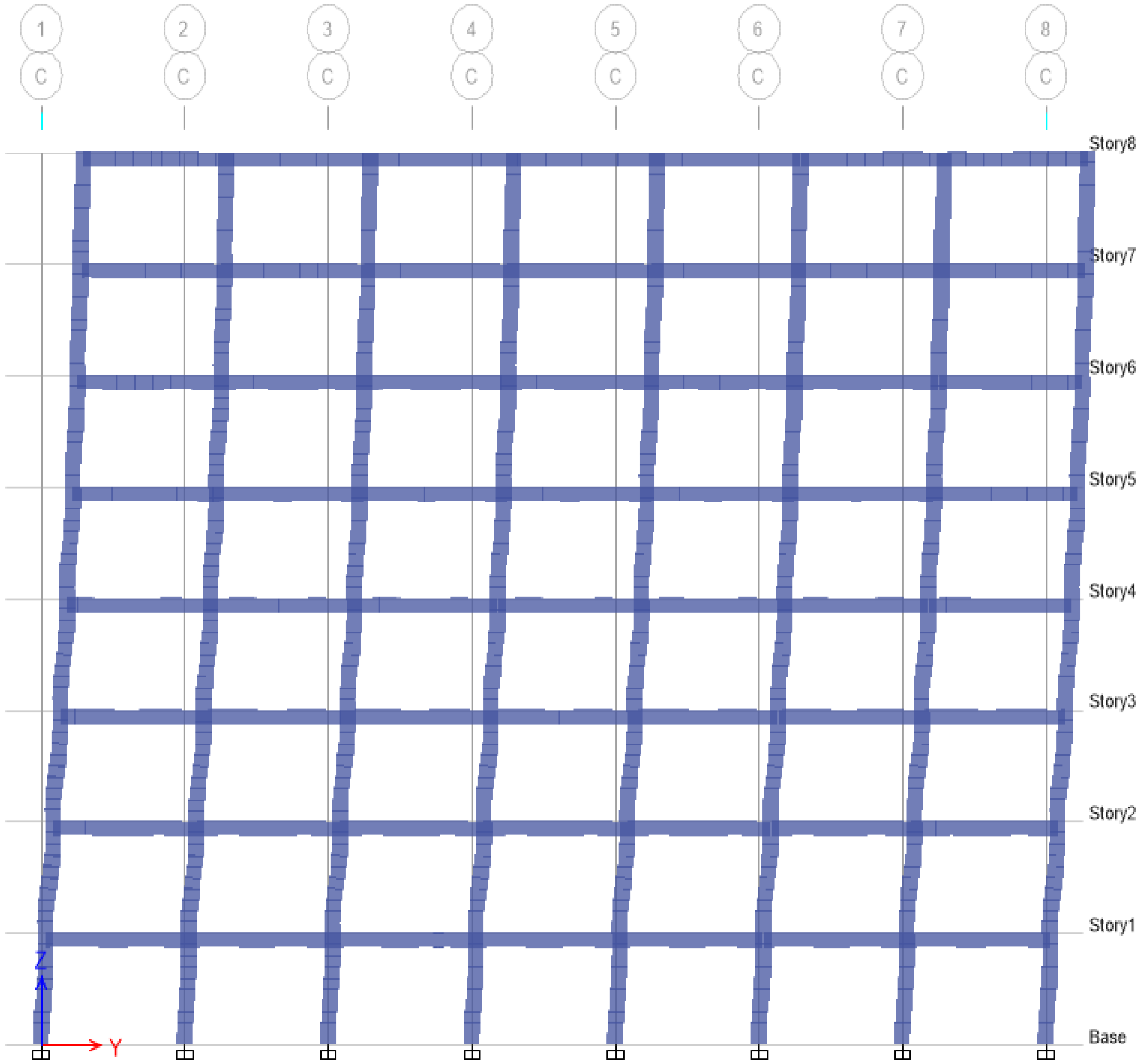
f) Irregular building with S2 staircase at corner



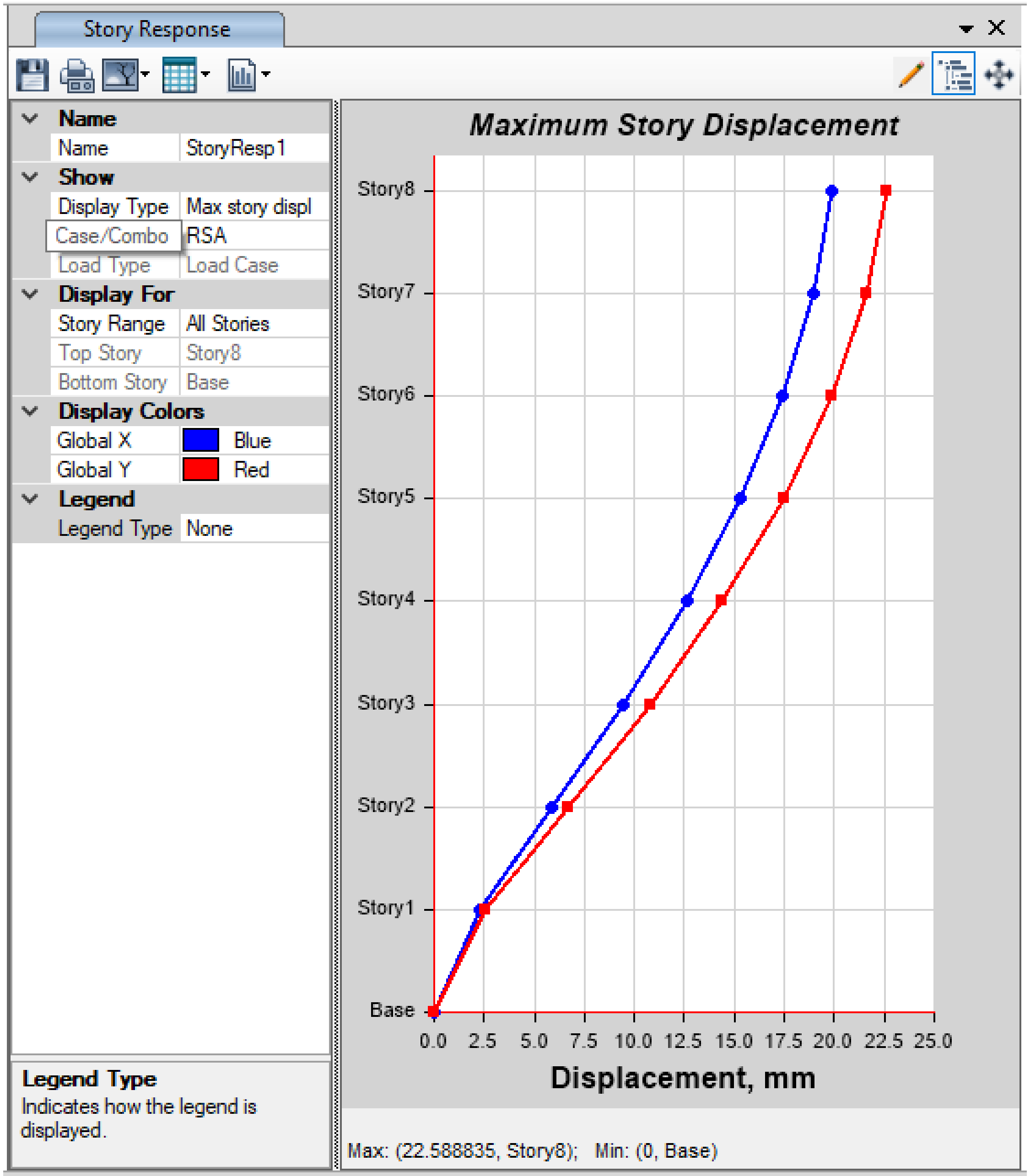
g) Irregular building with S3 staircase at corner



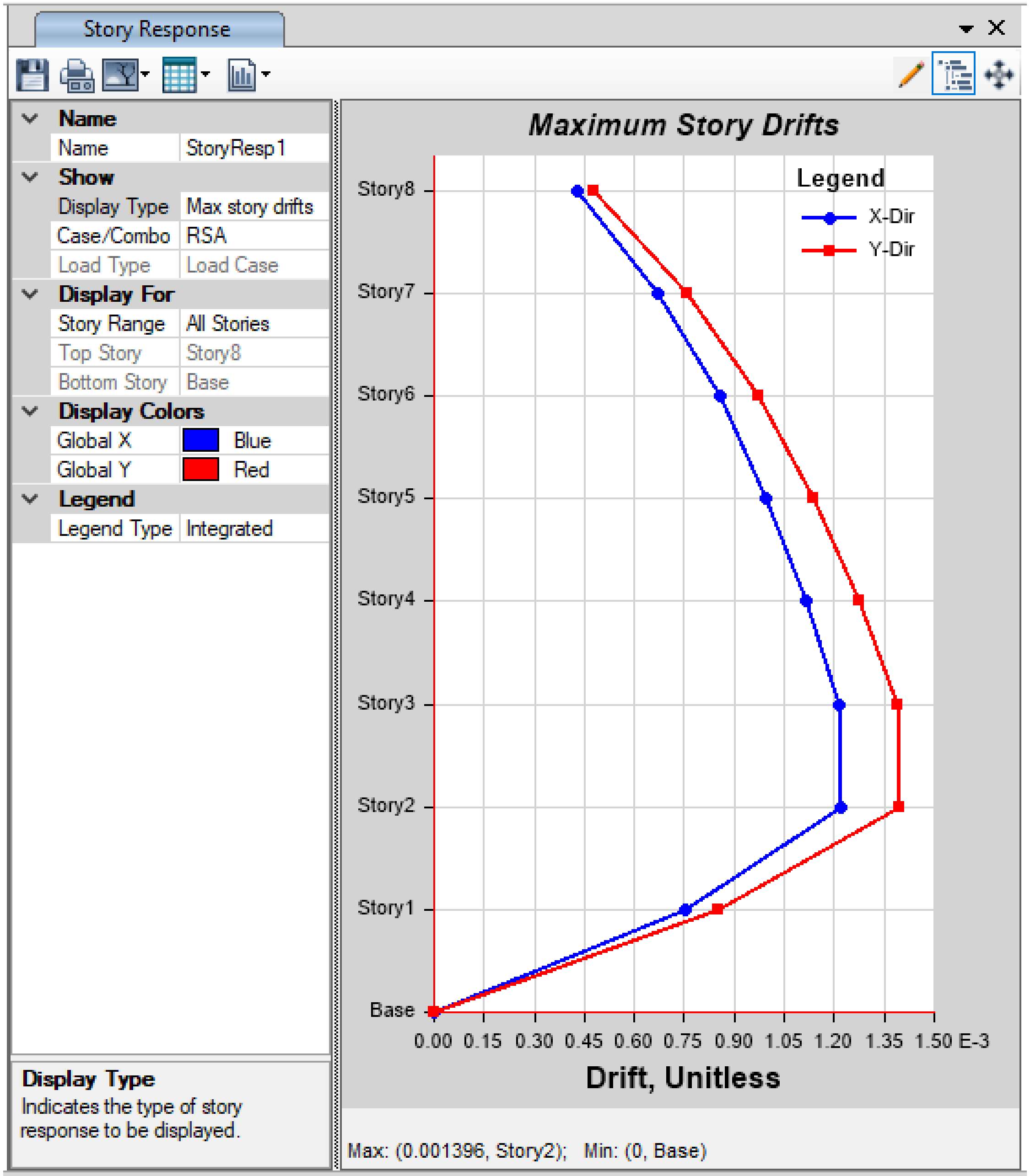
h) Irregular building with S4 staircase at corner



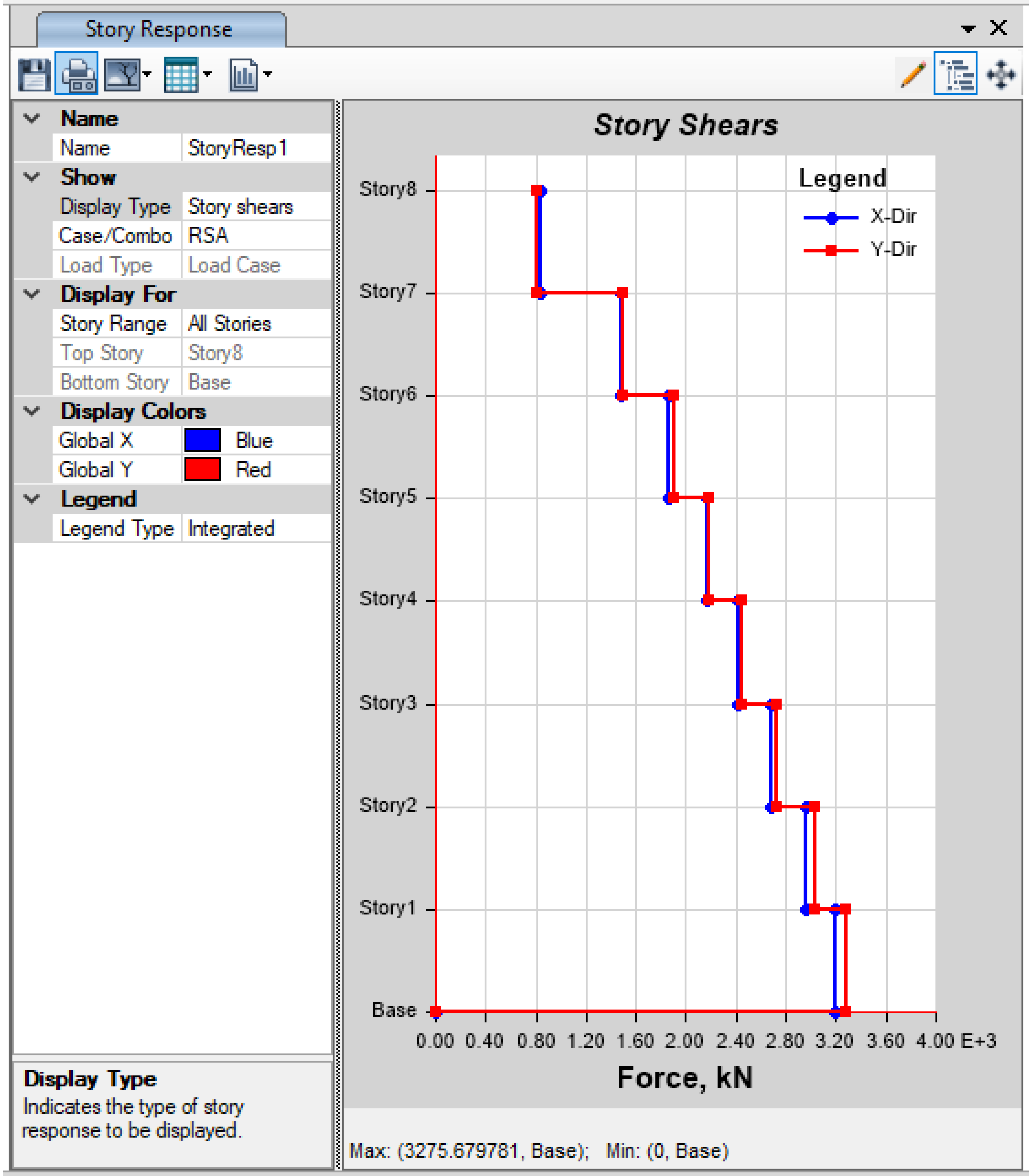
i) Deformed shape of frame section ETABS V.18



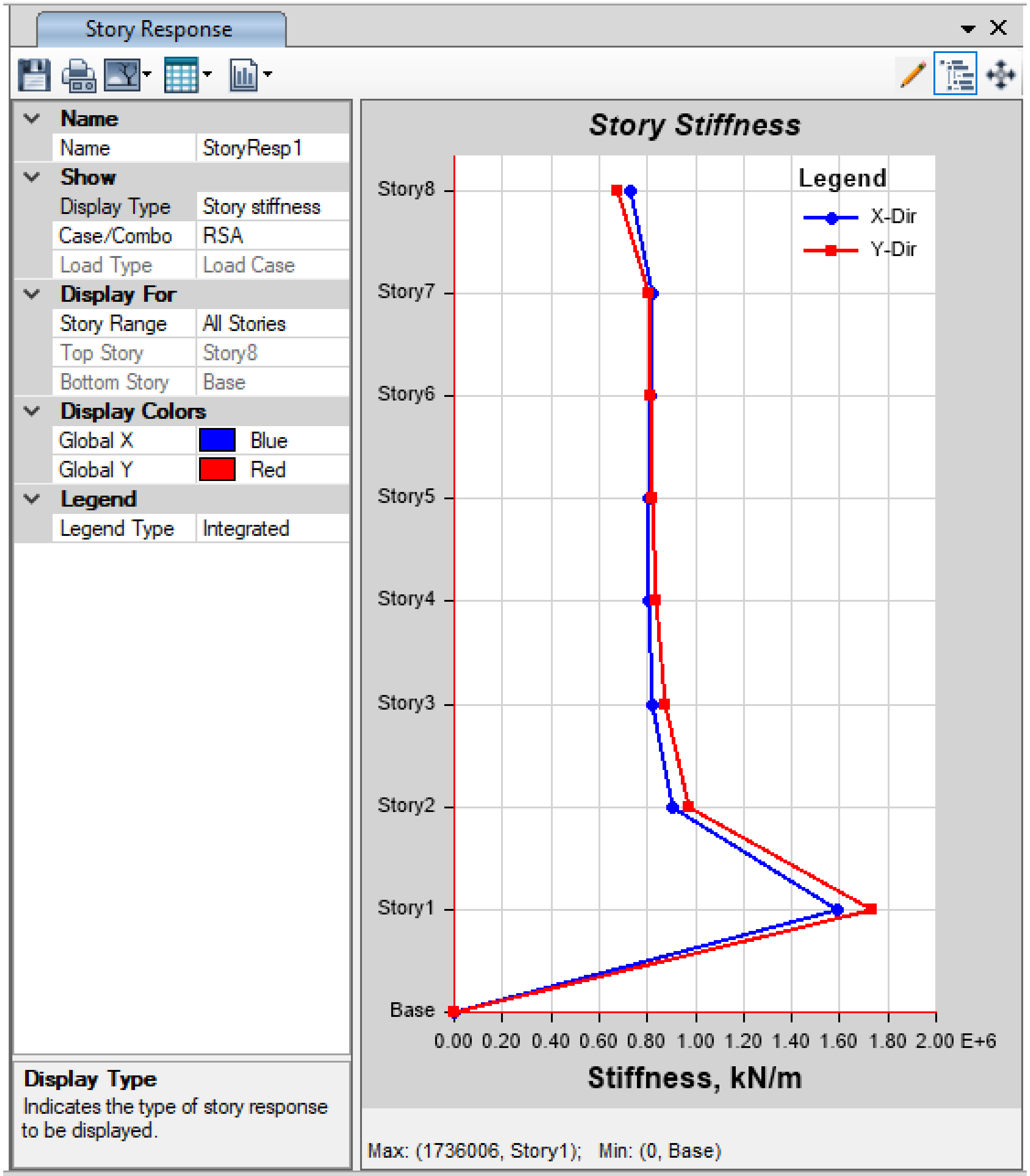
J) Story displacement graph drawn by ETABS V.18



k) Story drift graph drawn by ETABS V.18



l) Story shear graph drawn by ETABS V.18



m) Story stiffness graph drawn by ETABS V.18