# A STUDY OF LATERAL DRIFT CONTROL BY CONNECTING SKY BRIDGE BETWEEN TWO BUILDINGS

A Dissertation submitted in partial fulfillment of the requirement for the Award of degree of

**MASTER OF TECHNOLOGY**

**IN**

**STRUCTURAL ENGINEERING**

By


**NAMAN AGARWAL**

**Roll No. 2K15/STE/13**


Under the guidance of

**Dr. NIRENDRA DEV**

(Professor)


**Department of Civil Engineering**
**Delhi Technical University**
**(FORMERLY DELHI COLLEGE OF ENGINEERING)**


**JULY 2017**

## CANDIDATE'S DECLARATION

I hereby declare that the project work entitled **A Study of Lateral Drift Control by connecting Sky Bridge between two Buildings** submitted to Department of Civil Engineering, DTU is a record of an original work done by **Naman Agarwal** under the guidance of **Dr. Nirendra Dev**, Professor, Department of Civil Engineering, DTU, and this project work has not performed the basis for the award of any Degree or diploma/fellowship and similar project, if any.

**Naman Agarwal**

**(2K15/STE/13)**

**Department of Civil Engineering**
**Delhi Technological University**

# CERTIFICATE

This is to certify that the project entitled **A Study of Lateral Drift Control by connecting Sky Bridge between two Buildings** submitted by **Naman Agarwal,** in partial fulfillment of the requirements for award of the degree of **MASTER OF TECHNOLOGY (STRUCTURAL ENGINEERING)** to Department of Civil Engineering, DTU is the record of student's own work and was carried out under my supervision.

Date:

**(Dr. Nirendra Dev)**
Professor,
CED , D.T.U.

**Department of Civil Engineering**

**Delhi Technological University**

# ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my project guide and Head of Civil Engineering Department **Dr. Nirendra Dev** (Professor, Delhi Technological University) for giving me the opportunity to work on this topic. It would never be possible for me to complete this project without his precious guidance and his relentless support and encouragement. His interest in my work and appreciation of my efforts provided me with the constant motivation needed to achieve my goal. The cooperation, support and knowledge provided by the institute are duly acknowledged.

I am also thankful to all the faculty members and my classmates for the support and motivation during this work.

Last but not the least, I am thankful to my parents for their support and encouragement throughout my whole life.

# ABSTRACT

Nowadays Sky bridges are becoming very popular due to their aesthetics and the needs they serve like recreational facilities, a walkway, an evacuation option in the hour of disaster, etc. For structural purposes, controlling drift in a high rise structure is necessary. With the advent of sky bridges, engineers are looking forward to this option of controlling lateral response of the structures. To cater that need the study of controlling drift and displacement by providing sky bridge between two high rise buildings is performed here. Two high rise buildings 15m apart are analyzed without sky bridge first to find the maximum responses of the buildings such as drift and displacements. After that the buildings are connected by two sky bridges at $12^{th}$ and $20^{th}$ story level and the resulting structure is analyzed again. Two types of analysis are done, earthquake and wind analysis. For earthquake, static and dynamic (response spectrum) analysis and for wind only static analysis is performed. The software used for this study is ETABS 2015 which is a specific purpose software, analyzing and designing only buildings. The results obtained are then compared and conclusions are drawn later on.

# List of Tables

# List of Figures

# CONTENTS

# Chapter-1

# Introduction

## 1.1 General

Excess drift (the horizontal displacement) is one of the most serious issues in tall building design which is related to the dynamic characteristics of the building during earthquakes and strong winds (Wada 1992). The lateral wind load is usually the deciding factor in the structural design for super tall buildings. For very tall buildings wind pressure increases with height so lateral loads due to wind are larger than dead or live (imposed) loads. "Lateral (storey) drift is the amount of side sway between two adjacent stories of a building caused by lateral (wind and seismic) load. Horizontal deflection of a wall refers to its horizontal movement between supports under wind or earthquake loading. Vertical deflection of a floor or roof structural member is the amount of sag under gravity or other vertical loading."

It is the need of the hour to build sustainable cities that are friendly to the planet, its people and economic development. Sky Bridges satisfy this need. "A skyway, sky bridge, or skywalk is a type of pedway consisting of an enclosed or covered bridge between two or more buildings in an urban area" (Wikipedia 2017). It facilitates the movement of goods and individuals usually between or among buildings. In recent times, these structures, especially between buildings are rapidly gaining popularity owing to the increasing number of skyscrapers, their pleasing aesthetics, and the increasing demand of alternative evacuation routes in case of an emergency. Thus their effects on structural behavior and design are needed to be understood. Sky bridges increase walking area and thus by providing more levels for horizontal movement, congestion at lower levels including ground levels can be significantly reduced. Skyways can be connected at first few floors above the ground-level floor (Wikipedia 2017), or at mid height, or near top floors or at roof level, or any combination of these. These structures can also save lives by providing multiple emergency escape routes for tall buildings subjected to fire or terrorist attacks (NewScientist 2006).

Figure1.1 Linked Hybrid, Beijing, China (Holl 2009)

### 1.2 Objectives of the study

1. Study of Sky Bridge and its use as an emergency evacuation route.
2. Comparison of lateral drift values of individual buildings with that of sky bridge is connecting those two buildings.

# Chapter-2

# Literature Review

## 2.1 Past Studies

One of the major issues in tall building design is the calculation of lateral drift. Many scholars have suggested various ways of lateral load calculation through their studies. Also many researchers in the past have done study on the lateral drift and have proposed new ways of resisting it. **Wada (1992)** proposed unit load method and a "Lagrangian multiplier λ, a structure improvement method for minimizing the lateral drift of tall buildings (complex or regular) caused by earthquakes or strong winds". The above method has an additional advantage that it can "analyze the source of displacement of certain point of structure" (Timeshenko and Gore 1977). Further he used Lagrangian multiplier λ to minimize the displacement of the building without altering the total weight of the structure. He theorized that sections of certain members can be changed to minimize the displacement at top keeping total weight same.

**Kareem et al. (1999)** presented an overview of structural systems that can reduce lateral drift in tall buildings. They suggested use of Outrigger systems, Belt systems and Tube systems. They also suggested the modification of a structural building to reduce lateral drift using auxiliary damping devices such as Tuned mass dampers, Tune liquid dampers, Impact dampers, Visco-elastic dampers, Friction systems, Metallic Dissipators, etc.

**Verma (2014)** calculated the wind pressure coefficients for sky bridge connected rectangular tall buildings by the wind tunnel studies carried out on rigid models for 0°, 45° and 90° incidence angles. "The models were tested in the closed circuit wind tunnel having a cross section of 1.3m (width) x0.85m (height), at Civil Engineering Department, Indian Institute of Technology Roorkee. Perspex sheet 5mm in thickness is used for making two building models each with square in plan having size of 50mm×50mm×300mm.The two models are connected by a sky bridge, which is also made of Perspex sheet. It was observed from the study that negative pressure on opposite faces gets increased considerably when the models are close to each other."

**Kim et al. (2009)** studied the interference effects of surrounding structures on a tall building. The authors, using wind tunnel experiments on two identical high rise models spaced apart, calculated the maximum and minimum local external wind pressure coefficients ($C_{pe}$) on a wall to quantify cladding wind loads. The paper also studies interference effects on smallest minimum pressure coefficients for various incident wind angles. They concluded that

i. Due to shielding effects, the along wind loads on principal building significantly decreases.
ii. The interfering building in an oblique configuration can cause severe negative wind pressures on the principal building.

**Kheyari and Dalui (2015)** presented a study on interference effects of wind on tall buildings using CFD package of ANSYS. The aspect ratio of the models used (ratio of heights of interfering buildings and principal buildings) was varied from 1:5 to 5:5 and the wind angle were gradually changed from 0° to 90° at an interval of 30°. They calculated the external wind pressure coefficients for the principal building for each of the aspect ratio and the incidence wind angles. They compared the results with that of an isolated building.

**McCall (2013)** submitted a dissertation which compares the results of structural analysis and optimization of skyscraper systems with hinge connected and roller connected sky bridges and extends the comparison to skyscraper systems without sky bridges. “A simplified skyscraper sky bridge model (SSSM), which identifies and includes only the dominant degrees of freedom (DOF’s) when assembling the structure stiffness matrix, was developed to do approximate analysis of such systems. This greatly reduces computational time and computer memory compared to traditional finite element models (FEM). The steps of the SSSM consisted of: 1) determination of mega column areas, 2) constructing the stiffness matrix, 3) evaluation of volume, weight, mass and period, 4) calculation of lateral force vectors, and 5) calculation of displacement and stress constraints. It was found that the SSSM was very accurate for displacements (translations and rotations), and core, mega column, outrigger, and sky bridge stress.”

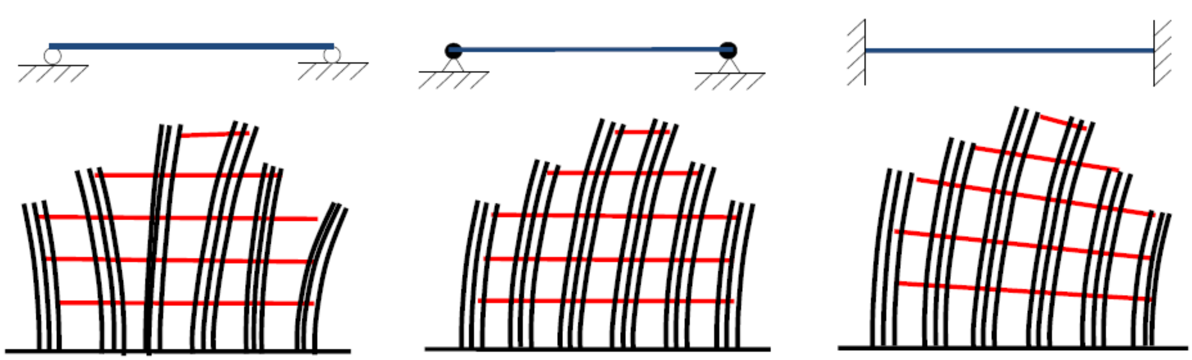
## 2.2 Theory

### 2.2.1 Sky bridges

Sky Bridges are types of elevated walkways consisting of enclosed bridge between two or more buildings usually in an urban area. In some Asian countries they usually connect rail stations or other transport with their own footbridges and run many kilometers. Skyways are usually connected on the first few floors above the ground-level floor, but sometimes they are much higher like in Petronas Towers, Malaysia. The space in the buildings connected by skyways is often devoted to retail business, so areas around the skyway may operate as a shopping mall. Non-commercial areas with closely associated buildings, such as university campuses, often have sky bridges between buildings (Wikipedia 2017).

### 2.2.2 Connections

The sky bridges should be properly connected to the main structure. There are three types of connections that are currently in use throughout the world. These include roller, hinge and rigid connections. One of the first sky bridges between skyscrapers, such as between the Petronas Towers in Malaysia, were connected to the skyscrapers with roller or slider connections. The sky bridge in Shanghai World Financial Center (SWFC) in Shanghai, China (Figure 2.3) is an example of rigid connections. The sky bridges connecting the three 42-story towers in Island Tower Sky Club in Fukuoka City, Japan (Figure 2.2) is an example of hinge connected sky bridges. Many examples can be found for rigid-connected sky bridges all over the world but examples of hinge-connected sky bridges are rare. (McCall 2013)



a) Roller b) Hinge c)Rigid

Figure 2.1 Types of Sky Bridge connections between skyscrapers (McCall 2013)

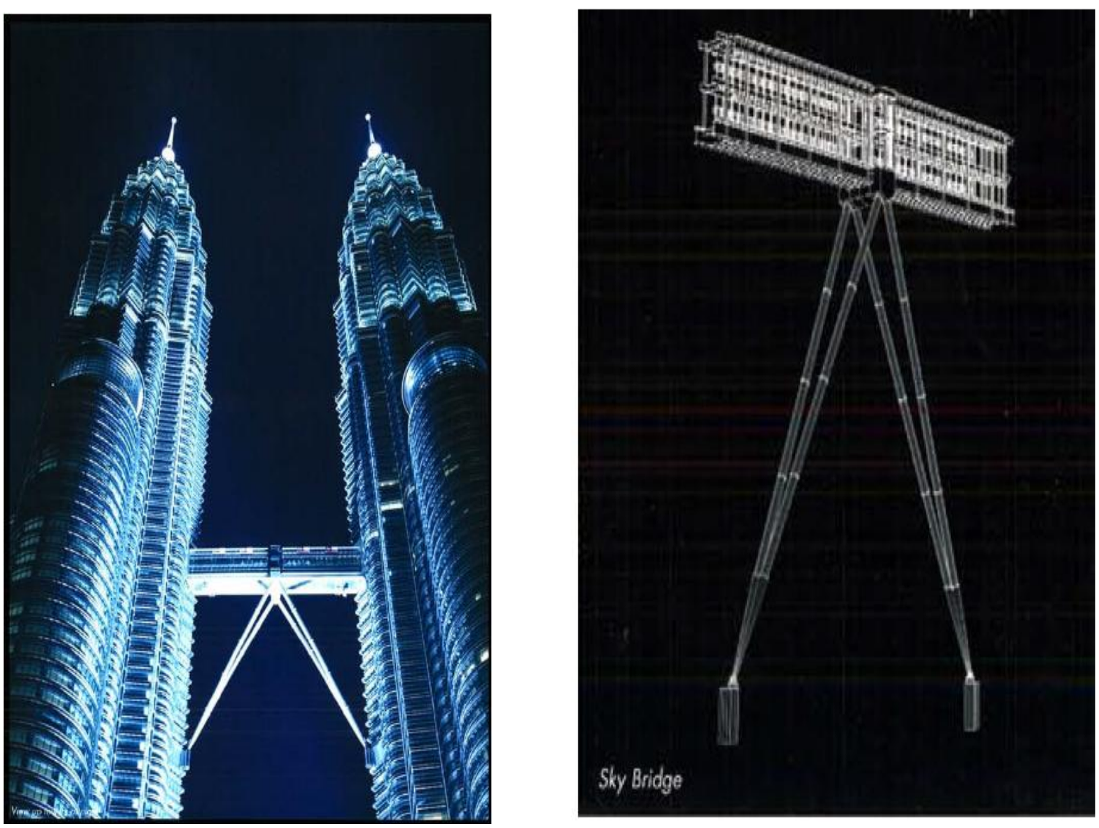
a) Bottom View of sky bridge                                        b) Elevation view

Figure 2.2 Island Tower Sky Club, Japan (Wikipedia 2010)

Figure 2.3 Shanghai World Financial Center (Panoramio 2012)

1. **Roller-Connected Sky bridges**

Roller-connected sky bridges allow the skyscrapers to sway independently under lateral loading (McCall 2013). One of the most famous examples of such a connection is the Petronas Twin Towers, shown in Figure 2.4, in Kuala Lumpur, Malaysia. Each 88-story tower, which is primarily used for office purposes, is 451.9 m high and connected at 41st story with a sky bridge. The bridge is two-level steel frame structure with large beams and columns that connect to continuous girders. The girders are connected with the towers with roller bearings which allow the towers to sway (or twist) independently of each other. An inverted V-shaped, two-hinged arc is connected to the sky bridge, thus supporting the bridge mid span. The bridge rise and fall as the towers move closer or further apart because of the rotational pin which is connecting the main bridge girders to the arch. (Abada 2004)




a) Elevation view b) Sky bridge Frame

Figure 2.4 Petronas Towers (Abada 2004)

Other examples of roller connected sky bridge include 'The Nina Towers in Hong Kong, China'. The structure consists of two towers, one 80 stories and one 42 stories which is roller-connected to a sky bridge at 41$^{st}$ story.

The 'Pinnacle@Duxton in Singapore' is a residential complex consisting of seven towers each with 50 stories. In this structure, each tower is connected at 26$^{th}$ and 50$^{th}$ stories to the adjacent towers with a sky bridge (Ming et al. 2010) as shown in Figure 2.5. Each tower is a reinforced beam-column-slab rigid frame structure in which no transfer beam is used and all loads are transferred directly to the foundation. The sky bridge in the structure consists of 3D triangular trusses made of steel with concrete slabs on top. (Engineers 2010)

a) Structural View b) Sky bridge Frame

Figure 2.5 Pinnacle@Duxton (Engineers 2010)

**2. Rigid-Connected Sky bridges**

Rigid-connected sky bridges are flexurally stiff sky bridges that are rigidly connected to the skyscrapers and constrain them to deflect as a cantilever unit (McCall 2013). One of the examples of rigid-connected sky bridge is 'The Shanghai International Design Center in Shanghai, China' which is a two tower connected building (Figure 2.6). The towers of building are of different heights. The towers are linked through a sky bridge which is connected at multiple stories. The sky bridge is a deep truss which forces the buildings to act in unison under lateral loads. (Lu 2009)

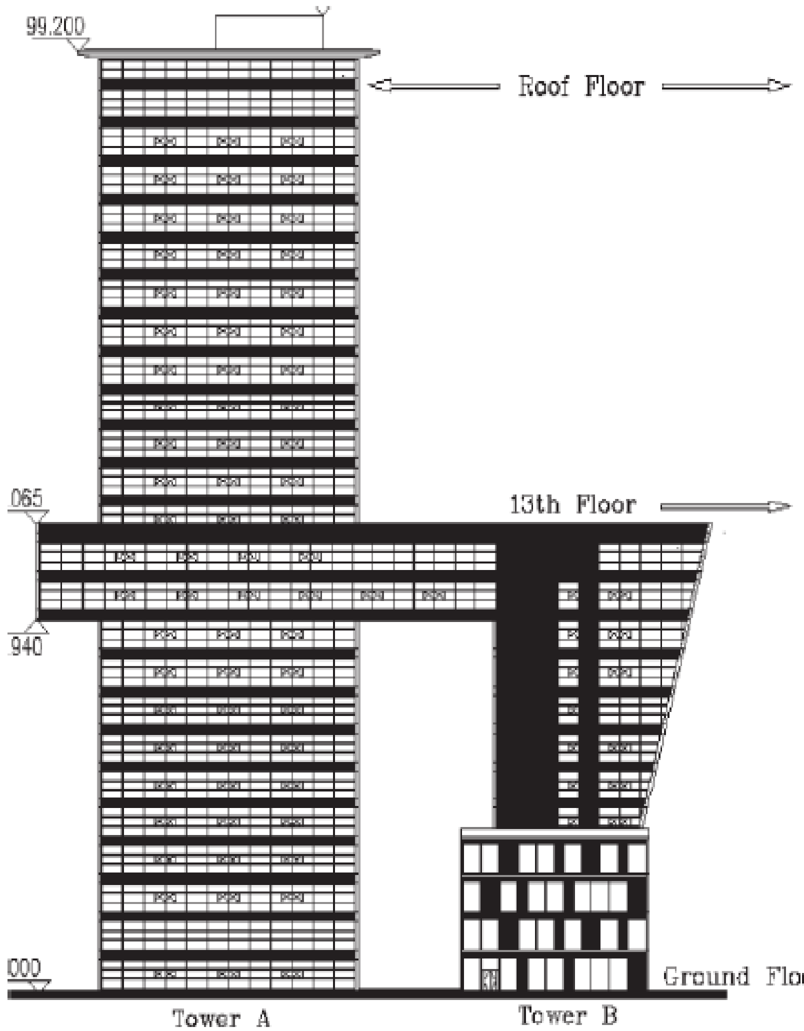



Figure 2.6 Shanghai International Design Center (Lu 2009)

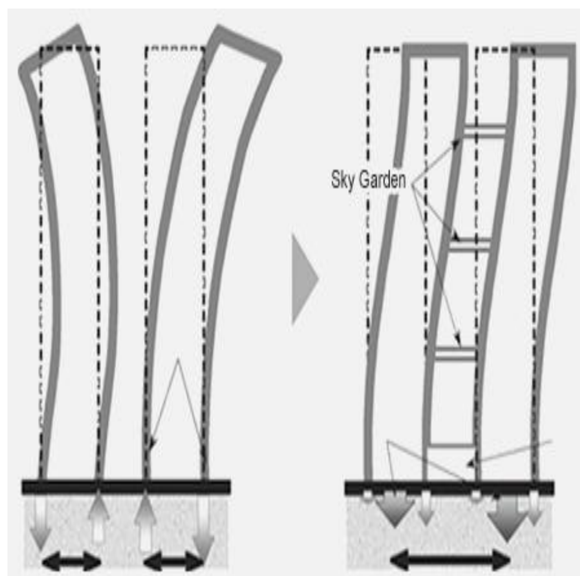
Other examples include ‘The Gate of the Orient in Suzhou, China’ which consists of an arch that connects the top eight stories of the two towers (Luong and Kwok 2012). The sky bridge of a building called The ‘China Central Television Headquarters (CCTV) in Beijing, China’ shown in Figure 2.7 is designed a bit differently from a typical bridge. It includes a combined system of a cantilevering overhang connecting the two towers with an ‘external continuous diagrid tube system, where the diagonal braces visually express the pattern of forces within the structure'. (Luong and Kwok 2012)

Figure 2.7 China Central Television Headquarters
(Luong and Kwok 2012)

**3. Hinge-Connected Sky bridges**

Hinge-connected sky bridges are axially stiff sky bridges that are hinge-connected to the skyscrapers which constrain the skyscrapers to sway in unison. The hinge-connected sky bridges are rare. If the span of the bridge is long then its behavior will be closer to the hinge connection rather than rigid connection (McCall 2013).

One of the examples of hinge-connected sky bridge is 'Island Tower Sky Club in Fukuoka City, Japan' as shown in Figure 2.8 (Wikipedia 2010) which consists of three towers each 42-story high. It is an apartment building. The building towers have three-fold rotational symmetry. The three towers are connected at the 15th, 26th and 37th stories by truss bridges. The structural specification of each tower is that it consists of a core wall at the center of the plan with perimeter columns and connecting beams. Vibration control dampers are used in the connection of the trusses with the towers. The dampers decrease the overturning response to lateral loads. The sky bridges are constructed of concrete slabs supported by steel trusses. (Nishimura 2011)




a) Elevation view (Wikipedia 2010) b) Sky bridge connections (Nishimura 2011)

Figure 2.8 Island Tower Sky Club

Other examples include ‘The Umeda Sky Building in Osaka, Japan’ shown in Figure 2.9. It is two 40 storied towers connected by an atrium platform at the top story with a large hole in the middle. It acts as an observation deck. The construction of the towers was completed first. The deck was then hoisted at the top of the. The behavior of the sky bridge is closer to hinge-connected because of its long span. (WikiArquitectura 2010)

Figure 2.9 Umeda Sky Building (WikiArquitectura 2010)

### 2.2.3 Purposes of Sky bridges

There are many purposes of sky bridges namely

*Evacuation and Safety*: The sky bridges linking towers can be used for horizontal evacuation at heights at the time of a fire, a bomb blast or any other terrorist attacks (Wood et al. 2005). Thus these can greatly increase the level of life safety for building occupants and can decrease the time taken by occupants to evacuate themselves or by emergency services. This can be understood with the figure shown below (Figure 2.10). In the first image, there is no sky bridge connected to the towers. The fire is spreading in the first building while the second building is safe. The occupants can only go downwards. The congestion on the bottom floors might hinder the proper evacuation. In the second image, the towers are linked through a sky bridge. Some of the occupants now have two options. They can either go downwards or they can go upwards and evacuate through the sky bridge to the next building which is safe. Now the second building may be used as a temporary camp. This is achieved through refuge floors

(Wood et al. 2005). All new buildings which exceed 25 floors are required to have the refuge floor at every 25th floor of the building. This refuge floor serves the following purposes:

i. Place of rest for the evacuating occupants,
ii. Serve to protect elder/disabled persons until they are rescued
iii. Serve as a fire fighting base, etc.

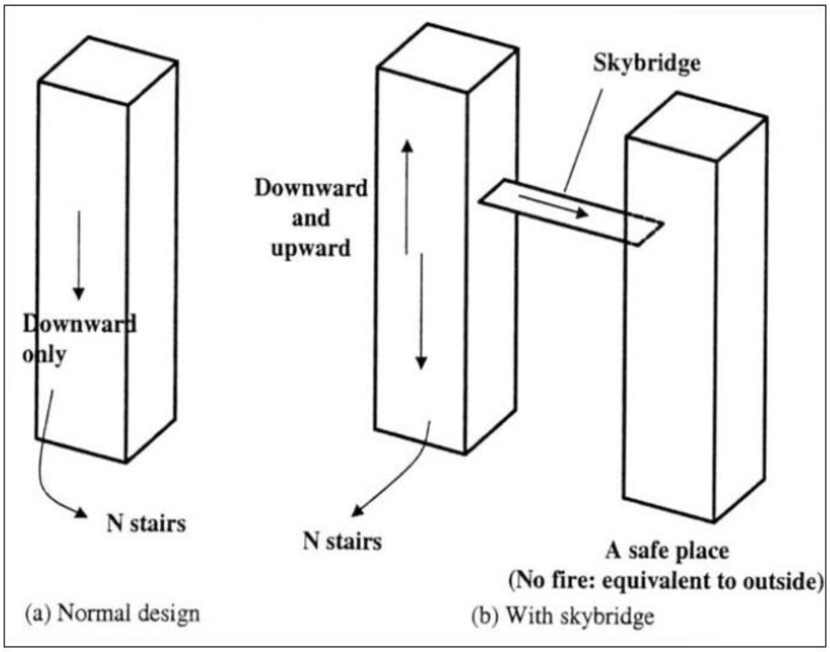



Figure 2.10 Evacuation in High rise buildings (Wood et. al 2005)

*Walkway*: Sky bridges are used as walkways. These increase walkability and reduce ground level congestion by providing more levels for horizontal movement. These connect several public buildings to provide easy access to commuters and can be used to connect private buildings for the use of employees and staff.

*Recreational facilities and aesthetics:* Other than the uses mentioned above the sky bridges can serve as a house to recreational centers like gym club, swimming pools, fitness centers, jogging track , party lounge, café, etc. The examples include Marina bay Sands, Singapore which has a sky bridge, called Sands SkyPark shown in Figure 2.11, connecting the top stories of the three towers. The sky bridge has a swimming pool, rooftop restaurants, club facilities, cantilevered observation deck, etc. There is a ‘Swimmable Sky Bridge’ at the top of the ‘Sky Habitat’, a two tower 38 storied apartment complex (Haklar 2009). The sky bridges connecting the towers of ‘The Linked Hybrid, Beijing, China’ houses a swimming pool, a café, a fitness room, a mini salon, etc (Holl 2009). The three sky bridges which connect the towers of ‘The Bahrain World Trade Center, Manama, Bahrain’(Figure 2.12) hold wind turbines. Also the use of sky bridges from the aesthetic point of view makes it popular among architects. (Haklar 2009)

Figure 2.11 Marina Bay Sands sky bridge-SkyPark (Haklar 2009)

a) Elevation view b) Sky bridge view

Figure 2.12 Bahrain World Trade Center (Haklar 2009)

*As a means to control lateral drift:* This is one of the most important purpose of a sky bridge from the structural point of view. The sky bridge provides a means of lateral resistance to the building towers. This is because it functions like a horizontal diaphragm (eg. floor slab). The floor slab system has very large stiffness in the horizontal direction. The sky bridges help to convey the lateral load into vertical structural elements such as ramparts and columns separated from opposing vertical load. (Kiran et al. 2016)

# Chapter 3
# Methodology

## 3.1 Introduction

The sky bridge has an important purpose for structural engineers. As mentioned earlier, it can control deflection of the structure upto a certain extent and using appropriate connections, can force the connected towers to deflect in unison. This chapter deals with the introduction of methods used to analyse the structure, namely static earthquake and wind analysis and dynamic earthquake analysis using response spectrum method. As discussed earlier, the deflections in structure can be caused by both earthquake and wind loads. So calculation of drift is necessary for both the cases. Later, the effects of presence of a building in the vicinity of another building shall be discussed. This is important because wind loads will be changed on either tower connected to sky bridge depending on the direction of wind and the distance between the towers. Also a brief introduction of the software used will also be given.

## 3.2 Earthquake loading

Earthquake loads consists of inertia forces of building mass that results from the shaking of its foundation by earthquake. The earthquake resistant design is generally focused on lateral forces as vertical and rotational components are not as severe as translational component of earthquake forces. The intensity of earthquake is inversely related to their frequency of occurrence. Severe earthquakes are rare, moderate ones occur more often and minor ones are frequent. According to IS 1893 (Part 1)-2002, earthquake resistant building is designed for Design Basis Earthquake which is half that of Maximum Considered Earthquake. Thus, the building should resist minor earthquake without damage, moderate ones with no structural damage but non-structural damage may happen and strong ones with a chance of both structural and non-structural damage but without collapse. The buildings which provide post earthquakes emergency services like hospital should be stronger. It is considered in the code as Importance factor. Now some basic earthquake terminology is given below. Earthquake analysis can be done using static methods as well as dynamic methods, which is discussed later on.

### 3.2.1 Basic Terminology (IS 1893 (Part 1)-2002)

*i.* *Damping:* "The effect of internal friction, imperfect elasticity of material, slipping, sliding etc. in reducing the amplitude of vibration and is expressed as percentage of critical damping."

ii. *Design Basis Earthquake: "*It is the earthquake which can reasonably be expected to occur at least once during the design life of the structure."

*iii.* *Importance Factor (I):* "It is a factor used to obtain the design seismic force depending on the functional use of the structure, characterised by hazardous consequences of its failure, its post-earthquake functional need, historic value, or economic importance."

*iv.* *Intensity of Earthquake:* "The intensity of an earthquake at a place is a measure of the strength of shaking during the earthquake, and is indicated by a number according to the modified Mercalli Scale or M.S.K. Scale of seismic intensities."

*v.* *Maximum Considered Earthquake ( MCE ):* "The most severe earthquake effects considered by IS 1893 (Part 1)-2002."

*vi.* *Modal Mass ($M_k$):* "Modal mass of a structure subjected to horizontal or vertical, as the case maybe, ground motion is a part of the total seismic mass of the structure that is effective in mode ***k*** of vibration. The modal mass for a given mode has a unique value irrespective of scaling of the mode shape."

*vii.* *Modal Participation Factor ($P_k$): "*Modal participation factor of mode ***k*** of vibration is the amount by which mode ***k*** contributes to the overall vibration of the structure under horizontal and vertical earthquake ground motions. Since the amplitudes of 95 percent mode shapes can be scaled arbitrarily, the value of this factor depends on the scaling used for mode shapes."

*viii.* *Mode Shape Coefficient ($\Phi_{ik}$):* "When a system is vibrating in normal mode ***k,*** at any particular instant of time, the amplitude of mass **i** expressed as a ratio of the amplitude of one of the masses of the system, is known as mode shape coefficient ($\Phi_{ik}$)."

ix. *Natural Period* (*T*): "Natural period of a structure is its time period of undamped free vibration."

x. *Response Reduction Factor (R):* “It is the factor by which the actual base shear force, that would be generated if the structure were to remain elastic during its response to the Design Basis Earthquake (DBE) shaking, shall be reduced to obtain the design lateral force.”

xi. *Seismic Weight (W):* “It is the total dead load plus appropriate amounts of specified imposed load.”

xii. *Structural Response Factors ( $S_a/g$ ):* “It is a factor denoting the acceleration response spectrum of the structure subjected to earthquake ground vibrations, and depends on natural period of vibration and damping of the structure.”

xiii. *Zone Factor (Z):* “It is a factor to obtain the design spectrum depending on the perceived maximum seismic risk characterized by Maximum Considered Earthquake ( MCE ) in the zone in which the structure is located.”

xiv. *Diaphragm:* “It is a horizontal, which transmits lateral forces to the vertical resisting elements, for example, reinforced concrete floors and horizontal bracing systems.”

**3.2.2 Static Analysis (IS 1893 (Part 1)-2002)**

The static method used in the present study is called equivalent lateral force procedure which uses approximate and simple estimate of structures’ fundamental period of vibration and expected maximum ground acceleration together with relevant factors to find maximum base shear. As per IS 1893 (Part 1)-2002, the base shear is given as

$$V_b = W * A_h \quad (1)$$

where

$$A_h = \frac{Sa}{g} * \frac{Z}{2} * \frac{I}{R} \quad (1a)$$

Note: For any structure with T<=0.1s, the value of $A_h$ will not be taken less than Z/2 whatever be the value of I/R.

For Importance factor, I following criteria will be used:

1. Important service and community buildings like schools and hospitals, fire stations, radio stations, etc. I=1.5
2. All other buildings, I=1

For zone factor, Z the figure 3.1 can be used

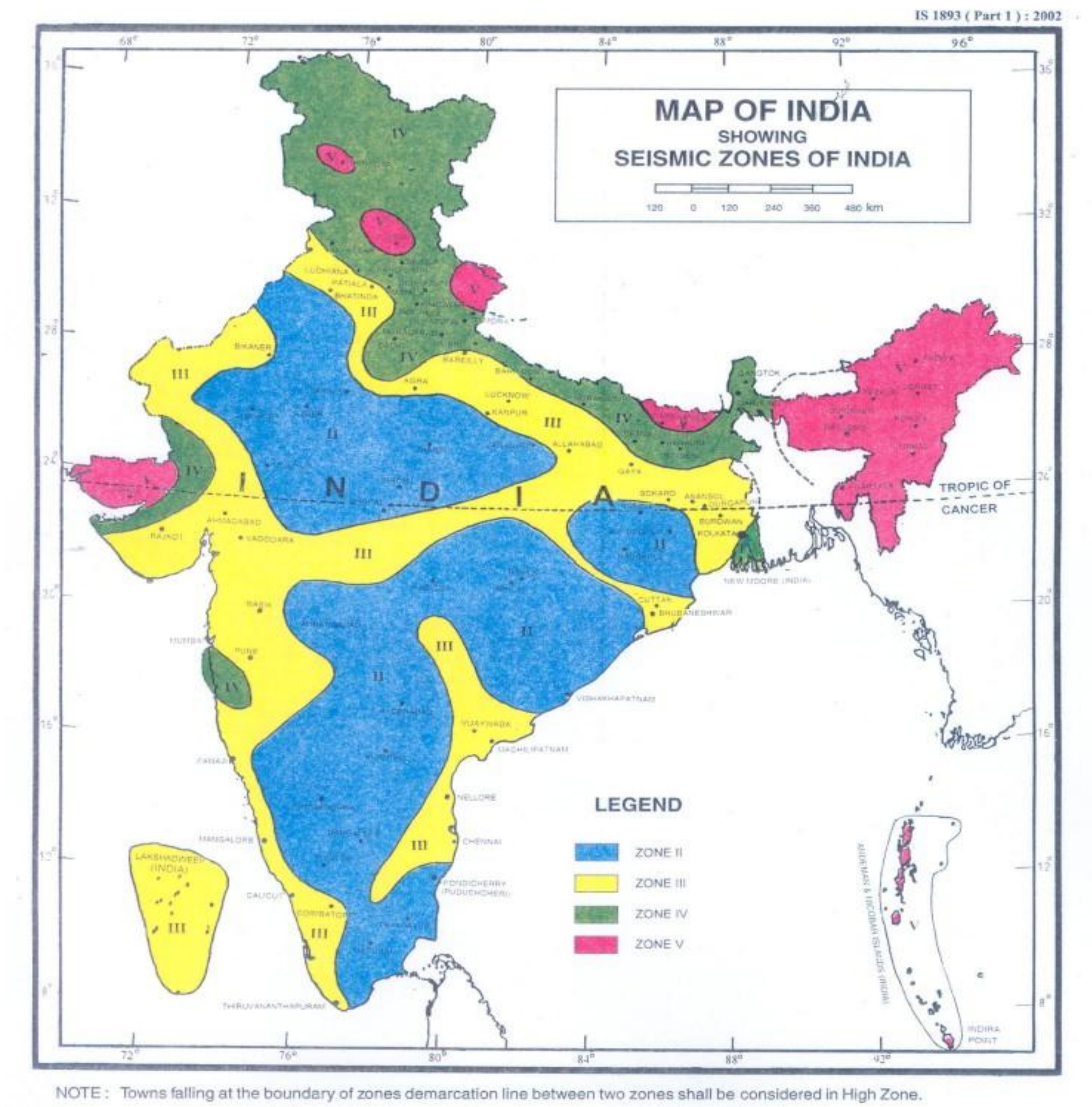



Figure 3.1 Seismic Zones of India (IS 1893 (Part 1)-2002)

Another way of getting zone factor, Z is from Table 3.1:

Table 3.1 Seismic zone factor

| Seismic zone | Intensity | Zone factor, Z |
|---|---|---|
| II | Low | 0.10 |
| III | Moderate | 0.16 |
| IV | Severe | 0.24 |
| V | Very Severe | 0.36 |

For response reduction factor, R values should be decided the structure is whether RC frame or Steel frame with or without shear walls or whether load bearing walls are present. Some typical values are given below in Table 3.2. In any case I/R value should not be taken greater than 1.

Table 3.2 Response reduction factors (IS 1893 (Part 1)-2002)

| | |
|---|---|
| Ordinary Moment Resisting RC frame (OMRF) | 3 |
| Special Moment Resisting RC frame (SMRF) | 5 |
| Ordinary Shear Wall with OMRF | 3 |
| Ordinary Shear Wall with SMRF | 4 |
| Ductile Shear Wall with OMRF | 4.5 |
| Ductile Shear Wall with SMRF | 5 |

$S_a/g$ values are dependent on the type of site the structure is present. The soil types could be rock or hard soil, medium soil and soft soil. The values could be taken from the graph given below in Figure 3.2 for calculated value of fundamental natural period (T) from equation (2).

The contribution of imposed load in calculation of seismic weight, W will be considered using Table 3.3

Table 3.3 Percentage of imposed loads to be used in seismic weight calculation

| Imposed load ($kN/m^2$) | Percentage of imposed load, % |
|---|---|
| Upto and including 3 | 25 |
| Above 3 | 50 |

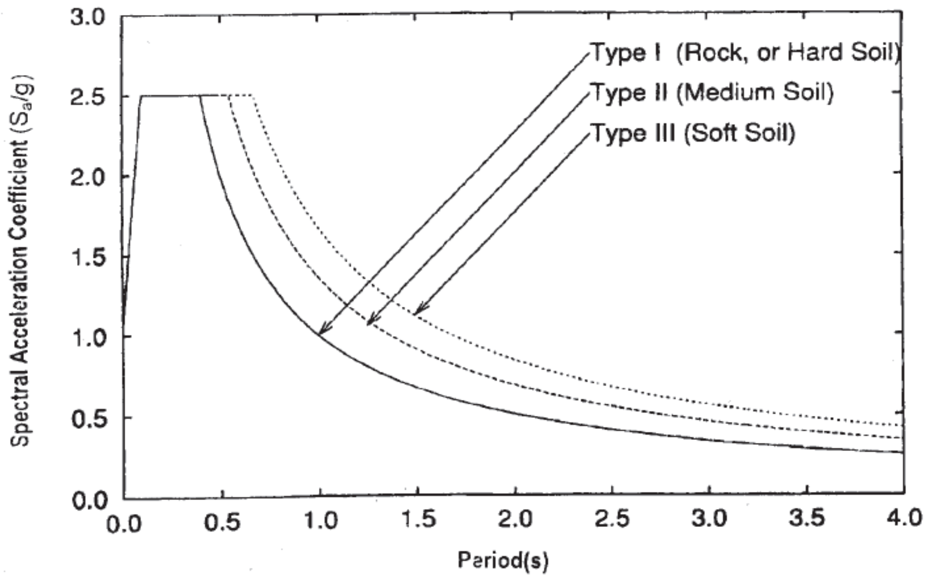



Figure 3.2 Response spectra for soil sites for 5% damping

The value of approximate fundamental natural time period ($T_a$) is calculated from the following formula:

i. For structure without brick infill panels

$T_a=0.075h^{0.75}$ RC frame

$T_a=0.085h^{0.75}$ Steel frame

ii. For all other buildings

$T_a=0.09/\sqrt{d}$ (2)

where h= Height of building, in m. This excludes the basement stories, where basement walls are connected with the ground floor deck or fitted between the building columns but it includes the basement stories, when they are not so connected.

d= Base dimension of the building at the plinth level, in m, along the considered direction of the lateral force.

The design base shear calculated in equation (1) will be distributed along the height of the building as per the following expression:

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2} \quad (3)$$

Note: The design lateral forces calculated in this analysis are less than the actual forces imposed on the building by the respective earthquake. This is because greater strength is provided by working stress levels, damping by building components and reduction in forces due to effective ductility of the structure as members yield beyond their elastic limit.

### 3.2.3 Dynamic Analysis

According to IS 1893 (Part 1)-2002 dynamic analysis shall be done for the following buildings:

i. Regular buildings: Those greater than 40 m in height in Zones IV and V and those greater than 90 m in height in Zones II and III.

ii. Irregular buildings: All framed buildings higher than 12m in Zones IV and V and those greater than 40m in height in Zones II and III.

There are two methods of dynamic analysis as per IS 1893 (Part 1)-2002

1. *Time History Method*: "It is an analysis of the dynamic response of the structure at each increment of time, when its base is subjected to a specific ground motion time history. Accelerograms at the ground surface are needed for input into the analyses. All accelerograms selected for the analyses must be compatible with the design earthquake scenario, the seismic-tectonic environment of the region, the geology of the area and geotechnical details in relation to the overlying soil particles of the sites." (Lam et al. 2007)
2. *Response Spectrum Method*: "The representation of the maximum response of idealized single degree freedom systems having certain period and damping, during earthquake ground motion is called response spectrum. The maximum response is plotted against the undamped natural period and for various damping values, and can be expressed in terms of maximum absolute acceleration, maximum relative velocity, or maximum relative displacement." Dynamic analysis done in this study is Response Spectrum method.

### 3.2.4 Response Spectrum Method

It is possible that buildings with different periods of vibration will respond in different ways to the same earthquake ground motion. Also a particular building will deflect differently during different earthquakes. Thus for design purposes it is required to represent the building's range of responses to different periods of ground motion. As per IS 1893(Part 1)-2002, the design base shear ($V_B$) obtained through this method shall be compared with the base shear computed from ($V_B^{'}$) computed from $T_a$ using equation (2). Where $V_B$ is less than $V_B^{'}$, all response quantities shall be multiplied by $V_B^{'}$/ $V_B$. Also the values of damping will be taken as 2% and 5% of the critical for steel and RC building respectively. The procedure for response spectrum method as per Indian code is given below:

1. After a design spectrum is selected, the modes and their periods of vibration are computed. The number of modes to be used in the analysis should be such that the sum total of modal masses of all modes considered is at least 90 percent of the total seismic mass and missing mass correction beyond 33 percent.
2. The response of the building from the spectrum for the period of each mode is determined.
3. From the curve representing single-degree-of-freedom response, participation of each mode is calculated.
4. Since the structure follows multiple degree of freedom (MDOF) system, the effects of modes are added to determine the peak response.
5. The maximum response so obtained is transformed to shears and moments that are used in the design of the building.

The commonly used methods for obtaining the peak response quantity are as follows:

1. *Absolute Sum Method (ABSSUM)*: In this method, "the peak responses of all the modes are added algebraically, assuming that all modal peaks occur at same time." The maximum response is given by

$$r_{max} = \sum_{i=1}^{n} |r_i|$$

   The Absolute sum method gives a very conservative estimate of resulting response quantity and hence provides an upper bound to peak value of total response.

2. *Square root of sum of squares method (SRSS)*: "The maximum response is obtained by square root of sum of square of response in each mode of vibration". The SRSS method gives good results when the modal frequencies are well separated. The only drawback is

it gives poor results if frequencies of contributing modes are very close together. It is expressed by

$$r_{max} = \sqrt{\sum_{i=1}^{n} r_i^2}$$

3. *Complete Quadratic Combination method (CQC)*: The expression is given by

$$r_{max} = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} r_i \alpha_{ij} r_j}$$

Where $r_i$ and $r_j$ are maximum responses in $i^{th}$ and $j^{th}$ mode respectively and $\alpha_{ij}$ is a correlation coefficient given by

$$\alpha_{ij} = \frac{8\left(\zeta_i \zeta_j\right)^{1/2}\left(\zeta_i + \beta \zeta_j\right)\beta^{3/2}}{(1-\beta^2) + 4\zeta_i \zeta_j \beta(1+\beta^2) + 4\left(\zeta_i^2 + \zeta_j^2\right)\beta^2}$$

Where $\zeta_i$ and $\zeta_j$ are damping ration in $i^{th}$ and $j^{th}$ modes of vibration respectively and

$$\beta = \frac{\omega_j}{\omega_j} \qquad (\omega_j > \omega_j)$$

The range of coefficient $\alpha_{ij}$ is $0 < \alpha_{ij} < 1$.

Regular or irregular plan configurations both can be modeled as a system of masses lumped at floor levels with each mass having one degree of freedom ( lateral displacement) at each floor level in the direction under consideration. Thus

i. *Modal Mass:* The modal mass $M_k$ is given by

$$M_k = \frac{\left[\sum_{i=1}^{n} W_i \varphi_{ik}\right]^2}{g \sum_{i=1}^{n} W_i \phi_{ik}^2}$$

Where g = acceleration due to gravity

$W_i$ = seismic weight of floor i

$\Phi_{ik}$ = Mode shape coefficient at floor i in mode k

ii. *Modal Participation Factors:* The modal participation factors are given by

$$P_k = \frac{\sum_{i=1}^{n} W_i \phi_{ik}}{\sum_{i=1}^{n} W_i \phi_{ik}^2}$$

Now the design lateral force at each level due to each mode is given by

$$Q_{ik} = A_k \phi_{ik} P_k W_i$$

Where $A_k$ =Design horizontal acceleration spectrum value using natural period of vibration $T_k$ of mode k

### 3.2.5 Procedure for dynamic analysis in ETABS

The dynamic analysis done by ETABS is precise. The software calculate the lateral forces and story shears using the expressions and specifications given in IS 1893 (part 1)-2002. The procedure is as follows:

1. A dynamic function is required to be specified in the software for the analysis. Seismic zone and soil type parameters are input in this function.
2. In Modal Cases dialog box, the no of modes are specified.
3. In Load cases menu, define a new function for response spectrum.
4. In this acceleration as Load Type is specified. The acceleration as ground motion is specified in the directions earthquake is to be expected.
5. Initial Scale factor is also specified which is given by $\frac{Ig}{2R}$ where I is importance factor, g is acceleration due to gravity and R is response reduction factor.
6. Now modal combination method, as per Indian code CQC is specified because the dispersion of modal frequencies before the analysis is unknown.
7. Diaphragm eccentricity and damping is specified. Also if the directions of ground motion specified in step 4 are orthogonal in nature then under Directional Combination Type SRSS is specified as per IS 1893 (part 1)-2002.
8. Now the analysis is performed.
9. Now check the results of modal participation mass ratios. If the sum is less than 90% for translational and rotational component, in step 2, no of modes are increased.
10. Also base shear is checked. In most of the cases, base shear due to dynamic analysis would be less than static analysis in initial run. To rectify that change step 5. The

scale factor will be multiplied by ratio of base shear due to static analysis to dynamic analysis.

11. Repeat step 8.
12. Check steps 8 and 9. If all ok, the results (in this study, the results are story drifts) are reported. If not, then rectify steps 2 and 5 and perform analysis again.

### 3.3 Wind loading

Wind load on a tall building acts over a large surface area and with a greater intensity at greater height and the lever arm about the base increases with increase in height. It has a dominant effect on structural arrangement and design of a tall structure. For assessing the wind load applied on a building, its motion has to be considered. Wind loads are pretty random. These are difficult to analyse from past events and cannot be predicted with confidence. Upto around 10 stories wind load rarely has any design effect on a building but above that wind loads could be critical. With the advent of architectural treatment, increase in strength of materials and advances in methods of analysis, the tall structures have become lighter and efficient, thus becoming more prone to deflection and swaying under wind loads. There are two approaches to analyse the tall buildings acting under wind load: dynamic analysis and static analysis. But first lets discuss some basic terminology.

#### 3.3.1 Basic Terminology (IS 875 (Part 3)-1987)

i. *Gust:* “A positive or negative departure of wind speed from its mean value, lasting for not more than, say, 2 minutes over a specified interval of time.”

ii. *Pressure coefficients:* “Pressure coefficient is the ratio of the difference between the pressure acting at a point on a surface and the static pressure of the incident wind to the design wind pressure, where the static and design wind pressures are determined at the height of the point considered after taking into account the geographical location, terrain conditions and shielding effect. The pressure coefficient is also equal to $[1 - (V_D/P_z)^2]$, where $V_D$ is the actual wind speed at any point on the structure at a height corresponding to that of $V_z$. Positive sign of the pressure coefficient indicates pressure acting towards the surface and negative sign indicates pressure acting away from the surface.”

iii. *Shielding Effect:* “Shielding effect or shielding refers to the condition where wind has to pass along some structure(s) or structural element(s) located on the upstream wind side, before meeting the structure or structural element under consideration. A factor called ‘shielding factor’ is used to account for such effects in estimating the force on the’ shielded structures.”

iv. *Terrain category:* “Terrain category means the characteristics of the surface irregularities of an area which arise from natural or constructed features. The categories are numbered in increasing order of roughness.”

v. *Velocity Profile:* “The variation of the horizontal component of the atmospheric wind speed at different heights above the mean ground level is termed as velocity profils.”

vi. *Topography*: “The nature of the earth’s surface as influenced the hill and valley configurations.”

vii. *P-Δ effect:* “These are the additional overturning moments applied to the structure resulting from seismic weights ‘P’ supported by the structure, acting through the lateral deflections, Δ, which directly results from horizontal forces. They are second order effects which increase the displacements, the member actions and lengthen the effective fundamental period of the structure.” (Davidson et al. 1992)

### 3.3.2 Dynamic Analysis

Dynamic analysis is done for buildings which are either exceptionally slender or tall or are located in severe exposure conditions, thus increasing the wind loads on buildings due to dynamic interaction between motion of the building and the gust of the wind. One of the methods to perform dynamic analysis of a tall building is ‘Wind Tunnel test’ which is widely accepted today.

### 3.3.3 Static Analysis

Static analysis is performed according to the Indian code IS 875 (Part 3)-1987. The design wind speed, at any height z, is based on three factors:

a) Risk level,

b) Terrain roughness, height and size of structure,

c) Local Topography

The expression is given by

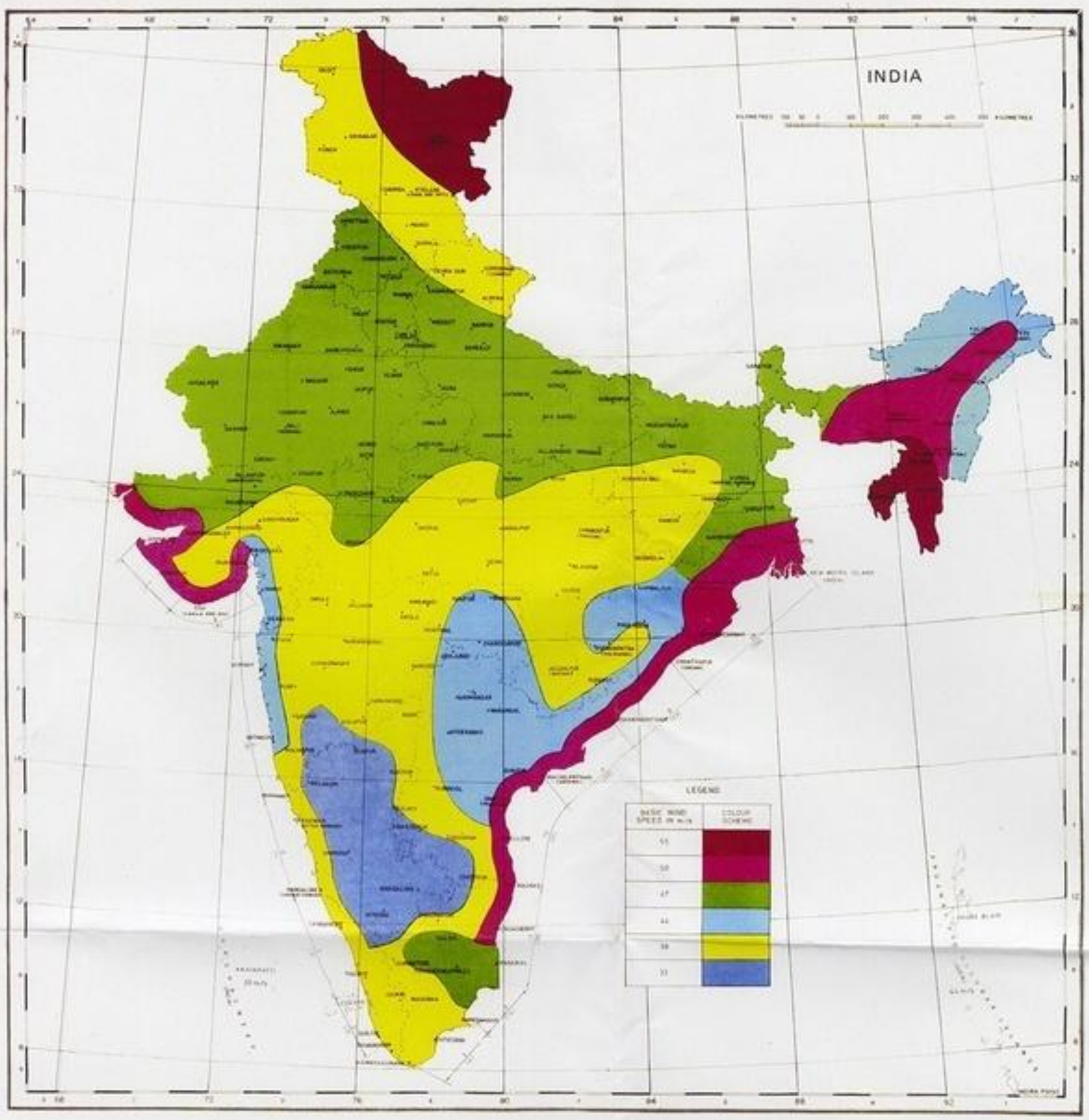
$$V_z = k_1 k_2 k_3 V_b$$

Where $V_b$ is the basic wind speed at 10m height which can be obtained from Figure 3.3, $k_1$ is probability factor (risk coefficient) (Table 3.4) , $k_2$ is terrain, height and size factor (Figure 3.4), $k_3$ is topography factor.

1. Terrain: Terrain categories are based on the number and spacing of obstructions from the principal structure. There are four categories, namely
   i. Category 1: Exposed open terrain with no or few obstructions, the height of obstructions surrounding the structure is less than 1.5m. Examples-open sea coasts and flat treeless plains.
   ii. Category 2: Open terrain with uniformly scattered obstructions of height 1.5m to 10m. Example- airfields, open parklands and undeveloped outskirts of towns and suburbs.
   iii. Category 3: Terrain with numerous closely spaced obstructions upto 10m height. Also terrains with a few isolated tall structures come under this category. Example- towns and industrial areas.
   iv. Category 4: Terrain with numerous tall closely spaced obstructions. Example: Large city centers and well developed industrial complexes.

2. Structure Class:
   i. Class A: Structures or their components having maximum dimension less than 20m
   ii. Class B: Structures or their components having maximum dimension between 20m and 50m.
   iii. Class C: Structures or their components having maximum dimension greater than 50m.

3. Topography: It includes the general level of site above sea level. The effect of topography is to accelerate wind near the summits of hills or crest of cliffs, escarpments or ridges and decelerate the wind in valleys or near the foot of cliffs or ridges. The value of $k_3$ is taken as 1 when upwind slope is up to 3°.For angles more than 3°, values can be taken between 1 and 1.36.




Based upon Survey of India map with the permission of the Surveyor General of India.

The territorial waters of India extend into the sea to a distance of twelve nautical miles measured from the appropriate base line.

Responsibility for the correctness of Internal details shown on the map rests with the publisher.

The boundary of Meghalaya shown on this map is as Interpreted from the North-Eastern Areas (Reorganization) Act, 1971, but has yet to be verified.

NOTE 1 — The occurrence of a tornado is possible in virtually any part of India. They are particularly more severe in the northern parts of India. The recorded number of these tornados is too small to assign any frequency. The devastation caused by a tornado is due to exceptionally high winds about its periphery, and the sudden reduction in atmospheric pressure at its centre, resulting in an explosive outward pressure on the elements of the structure. The regional basic wind speeds do not include any specific allowance for tornados. It is not the usual practice to allow for the effect of tornados unless special requirements are called for as in the case of important structures such as, nuclear power reactors and satellite communication towers.

NOTE 2 — The total number of cyclonic storms that have struck different sections of east and west coasts are included in Fig. 1, based on available records for the period from 1877 to 1982. The figures above the lines (between the stations) indicate the total number of severe cyclonic storms with or without a core of hurricane winds (speeds above 87 km/h) and the figures in the brackets below the lines indicate the total number of cyclonic storms. Their effect on land is already reflected in the basic wind speeds specified in Fig. 1. These have been included only as an additional information.



Figure 3.3 Basic wind speed map of India (IS 875(Part 3)-1987

Table 3.4 Risk Coefficient (IS 875(Part 3)-1987)

| Class of structure | $k_1$ factor for basic wind speed | | | | | |
|---|---|---|---|---|---|---|
| | 33 | 39 | 44 | 47 | 50 | 55 |
| All general buildings and structures | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Temporary sheds, structures such as those used during construction operations structures during construction stages and boundary walls | 0.82 | 0.76 | 0.73 | 0.71 | 0.70 | 0.67 |
| Buildings and structures presenting a low degree of hazard to life and property in the event of failure, farm buildings other than residential buildings | 0.94 | 0.92 | 0.91 | 0.90 | 0.90 | 0.89 |
| Important buildings and structures such as hospitals communication buildings / towers, power plant structure | 1.05 | 1.06 | 1.07 | 1.07 | 1.08 | 1.08 |

| Height | Terrain Category 1 Class | | | Terrain Category 2 Class | | | Terrain Category 3 Class | | | Terrain Category 4 Class | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m | A | B | C | A | B | C | A | B | C | A | B | C |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) |
| 10 | 1·05 | 1·03 | 0·99 | 1·00 | 0·98 | 0·93 | 0·91 | 0·88 | 0·82 | 0·80 | 0·76 | 0·67 |
| 15 | 1·09 | 1·07 | 1·03 | 1·05 | 1·02 | 0·97 | 0·97 | 0·94 | 0·87 | 0·80 | 0·76 | 0·67 |
| 20 | 1·12 | 1·10 | 1·06 | 1·07 | 1·05 | 1·00 | 1·01 | 0·98 | 0·91 | 0·80 | 0·76 | 0·67 |
| 30 | 1·15 | 1·13 | 1·09 | 1·12 | 1·10 | 1·04 | 1·06 | 1·03 | 0·96 | 0·97 | 0·93 | 0·83 |
| 50 | 1·20 | 1·18 | 1·14 | 1·17 | 1·15 | 1·10 | 1·12 | 1·09 | 1·02 | 1·10 | 1·05 | 0·95 |
| 100 | 1·26 | 1·24 | 1·20 | 1·24 | 1·22 | 1·17 | 1·20 | 1·17 | 1·10 | 1·20 | 1·15 | 1·05 |
| 150 | 1·30 | 1·28 | 1·24 | 1·28 | 1·25 | 1·21 | 1·24 | 1·21 | 1·15 | 1·24 | 1·20 | 1·10 |
| 200 | 1·32 | 1·30 | 1·26 | 1·30 | 1·28 | 1·24 | 1·27 | 1·24 | 1·18 | 1·27 | 1·22 | 1·13 |
| 250 | 1·34 | 1·32 | 1·28 | 1·32 | 1·31 | 1·26 | 1·29 | 1·26 | 1·20 | 1·28 | 1·24 | 1·16 |
| 300 | 1·35 | 1·34 | 1·30 | 1·34 | 1·32 | 1·28 | 1·31 | 1·28 | 1·22 | 1·30 | 1·26 | 1·17 |
| 350 | 1·37 | 1·35 | 1·31 | 1·36 | 1·34 | 1·29 | 1·32 | 1·30 | 1·24 | 1·31 | 1·27 | 1·19 |
| 400 | 1·38 | 1·36 | 1·32 | 1·37 | 1·35 | 1·30 | 1·34 | 1·31 | 1·25 | 1·32 | 1·28 | 1·20 |
| 450 | 1·39 | 1·37 | 1·33 | 1·38 | 1·36 | 1·31 | 1·35 | 1·32 | 1·26 | 1·33 | 1·29 | 1·21 |
| 500 | 1·40 | 1·38 | 1·34 | 1·39 | 1·37 | 1·32 | 1·36 | 1·33 | 1·28 | 1·34 | 1·30 | 1·22 |

Figure 3.4 Terrain, Structure class and height of structure ($k_2$) factors

After that design wind pressure intensity can be calculated at any height above mean ground level using the expression

$$p_z = 0.6V_z^2$$

Now wind load acting on a structural element is given by

$$F = \left(C_{pe} - C_{pi}\right)Ap_z$$

Where $C_{pe}$ is external wind pressure coefficient which can be determined experimentally.

$C_{pi}$ is internal wind pressure coefficient whose values are $\pm 0.2$ for wall openings less than 5%, $\pm 0.5$ for openings between 5% and 20% and $\pm 0.7$ for openings greater than 20%.

A is surface area of structural element.

### 3.3.4 Procedure for static wind analysis in Etabs

The static wind analysis is done by Etabs in two ways. The first method allows the user to input wind pressure coefficients on each face of the building. The second method allows the user to calculate lateral wind forces manually and applying it to slab diaphragms. This study is done by using first method only. The software calculate the lateral forces using the expressions and specifications given in IS 875 (part 3)-1987. The procedure is as follows:

1. First, wind load patterns are defined for assumed wind direction.
2. In the same dialog box, under 'Modify lateral Load', user can choose either the first method or second method of applying lateral loads.
3. Afterwards, specify Structure Class, Basic Wind Speed, Terrain Category and $k_1$ (risk coefficient) and $k_3$ (topography factor) factors. The software itself calculates $k_2$ factor with the variation in height of the structure and Structure Class and Terrain Category input by user.
4. Under Assign menu, specify the wind pressure coefficients from either IS 875 (part 3) 1987 or any verified earlier studies.
5. Define load combinations as per code and analyse. Check the story drifts as per specifications.
6. For sky bridges, apply manual loads as per IRC:6-2014.
7. Using Figure 3.5, calculate $V_z$ and $P_z$.

8. The transverse wind force is calculated using equation given below and appropriate forces are applied on corresponding centroidal area of the element. The values of various variables in the below equation can be obtained from IRC:6-2014.

$$F_T = P_z A_T G C_D$$

where , $P_z$ is the hourly mean wind pressure in $N/m^2$

$A_T$ is the solid area, G is the gust factor and $C_D$ is the drag coefficient.

9. The longitudinal force, $F_L$ on the beam element can be taken as 25% of the transverse wind load.

10. The upward or downward force on the centroidal area of the corresponding element can be taken as

$$F_v = P_z A_p G C_L$$

Where $A_p$ is the plan area, and $C_L$ is the lift coefficient and their values can be obtained from IRC:6-2014 as mentioned in step 8.

11. Analyse the structure and check for the story drifts.

| H (m) | Bridge Situated in | | | |
|---|---|---|---|---|
| | Plain Terrain | | Terrain with Obstructions | |
| | $V_z$ (m/s) | $P_z$ ($N/m^2$) | $V_z$ (m/s) | $P_z$ ($N/m^2$) |
| Up to 10 m | 27.80 | 463.70 | 17.80 | 190.50 |
| 15 | 29.20 | 512.50 | 19.60 | 230.50 |
| 20 | 30.30 | 550.60 | 21.00 | 265.30 |
| 30 | 31.40 | 590.20 | 22.80 | 312.20 |
| 50 | 33.10 | 659.20 | 24.90 | 373.40 |
| 60 | 33.60 | 676.30 | 25.60 | 392.90 |
| 70 | 34.00 | 693.60 | 26.20 | 412.80 |
| 80 | 34.40 | 711.20 | 26.90 | 433.30 |
| 90 | 34.90 | 729.00 | 27.50 | 454.20 |
| 100 | 35.30 | 747.00 | 28.20 | 475.60 |

Figure 3.5 Hourly mean wind speed and pressure (IS 875(Part 3)-1987

### 3.4 Software Used: ETABS 2015

ETABS is a software for design and static, nonlinear, dynamic and linear analysis, of structural systems specifically buildings. Multistorey buildings are very common in present times thus these require special programs for analysis as manual calculation could be very time consuming and tedious job.

The innovative and ground-breaking new ETABS is the ultimate integrated software suite for the structural analysis and design of buildings. ETABS possess innovative 3D object based demonstrating and visualization tools. It also offers a much faster linear and nonlinear analytical power compared to other analysis and design softwares like STAAD. The software also allows user to print analysis and design reports that are very easy to decipher. The results can be read in tabular and graphical form which are easy to understand.

The graphic user interface of the software allows swift and speedy generation of structural models using intuitive drawing commands. AutoCAD drawings can be transferred to ETABS models or vice versa. The numerical solution ETABS use is FEM which gives more accurate results compared to other softwares. The software have unique input and output techniques that serve specifically to building structures.

The need for special purpose programs like ETABS is greater in present times as structural engineers use non-linear dynamic analysis for more practical and realistic interpretation of behaviour of multistory buildings. Their analytical models are quite heavy that require greater computer power and are very time consuming. Thus ETABS reduce that computer memory consumption and allows a fast analysis and automated design of buildings using deisgn codes of various countries that the softwares constitutes in its very large database. ETABS is also capable of performing time variant earthquake analysis such as response spectrum analysis, time history analysis, etc. (CSI Knowledge Base 2010)

# Chapter 4

# Analysis and Results

## 4.1 Model

For analysis of present study, two buildings (G+25) are taken. The buildings and sky bridge is RC framed. The two towers without sky bridge are analyzed first individually, then analysis is done including sky bridge. The sky bridge is connected at 12$^{th}$ and 20$^{th}$ floor. The towers are 15m apart and 78.6m high. The following table presents the structural specifications of the towers and the structure.

Table 4.1 General Specifications

| Number of stories | G+25 |
|---|---|
| Plan dimension of a single tower in X direction | 27m |
| Plan dimension of a single tower in Y direction | 23m |
| Spacing between buildings | 15m |
| Total height of each tower | 78.6m |
| Single story height | 3m |
| Slab Thickness | 200mm |
| Shear Wall Thickness | 250mm |
| Column Size | 750x750 mm |
| Beam size: Towers<br>Sky bridge | 500x750 mm<br>250x450 mm |

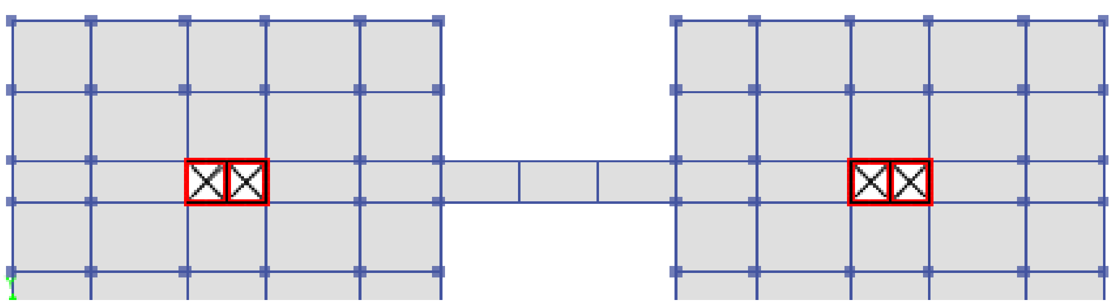


Figure 4.1 Plan of the model

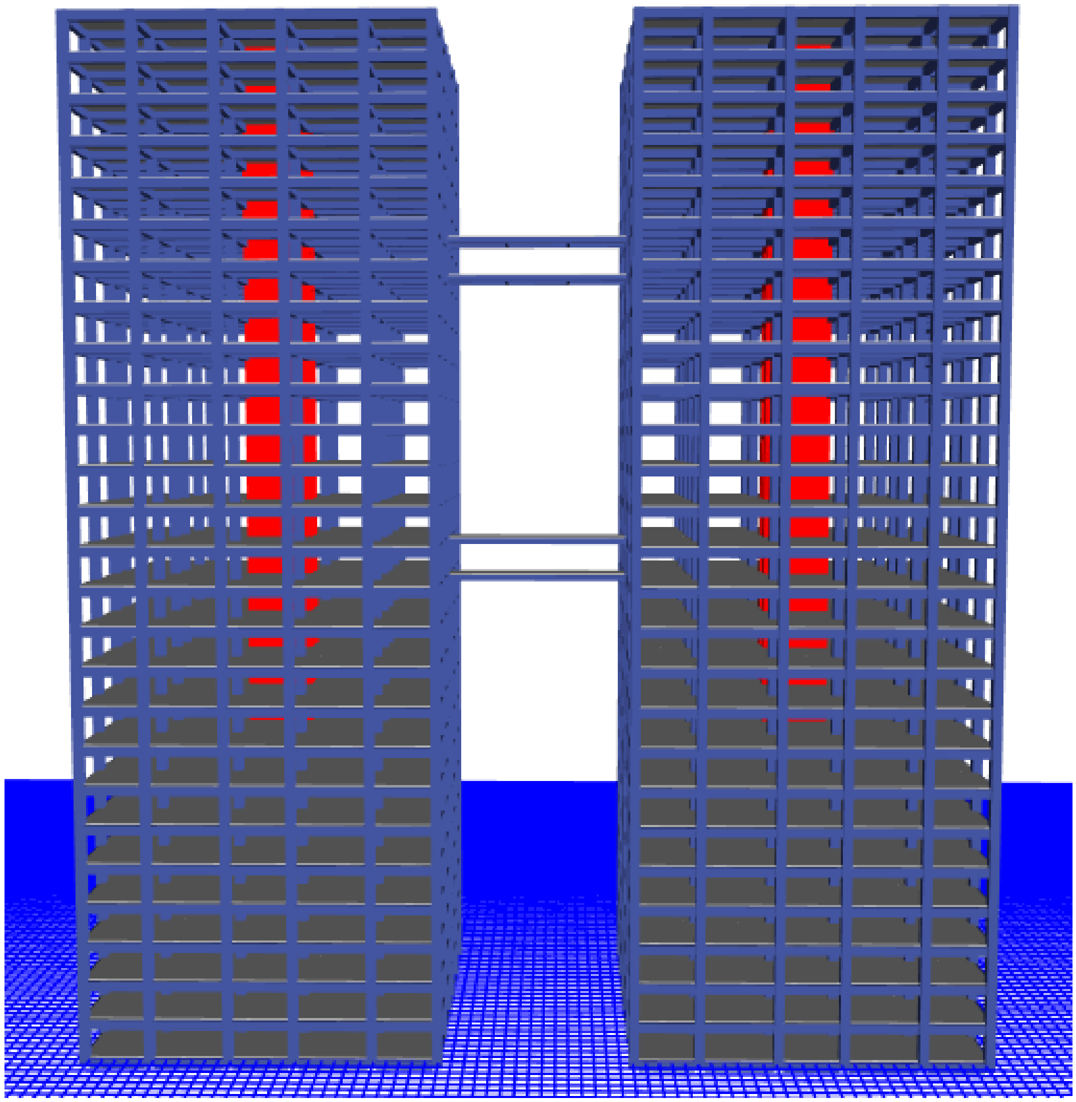


Figure 4.2 3D Rendered view of the model

### 4.1.1 Cracked RC section properties

Table 4.2 Cracked RC section Properties (CED 38(10639) WC)

| Structural Element | Moment of Inertia |
|---|---|
| Slabs | 0.25 $I_g$ |
| Columns | 0.7 $I_g$ |
| Beams | 0.35 $I_g$ |
| Walls | 0.7 $I_g$ |

### 4.1.2 Material Specifications

Table 4.3 Material Specifications

| | |
|---|---|
| Grade of concrete | M30 |
| Grade of steel | Fe415 |
| Density of Brick Masonry | 20 $kN/m^3$ |

### 4.1.3 Load Specifications

Table 4.4 Load Specifications

| | |
|---|---|
| Dead load | As per IS 875 (Part 1)-1987 |
| Live load | Roof: 1.5 $kN/m^2$<br>Other Floors: 3 $kN/m^2$<br>Sky Bridge: 5 $kN/m^2$ (as per IRC:6-2014) |
| Floor Finish | 1.5 $kN/m^2$ |
| Wind load | Towers: As per IS 875 (Part 3)-1987<br>Sky Bridge: As per IRC:6-2014 |
| Earthquake load | As per IS 1893 (part 1)-2002 |

### 4.1.4 Load Combinations

As per IS 1893 (part 1)-2002, following load combinations for Limit State has been used:

1. 1.5(DL+LL)
2. 1.2(DL+LL±EL)
3. 1.2(DL+LL±WL)
4. 1.5(DL±EL)
5. 1.5(DL±WL)
6. 0.9DL±1.5EL
7. 0.9DL±1.5WL

Note: i. For P-Δ analysis following load combination is used: 1.2(DL+0.5LL) (CSI Knowledge Base 2010)

ii. DL-dead load

iii. LL-live or imposed load

iv. EL/WL-earthquake load/wind load

### 4.2 Earthquake Analysis Parameters

The earthquake analysis is done by two methods: static and dynamic. Their input parameters are given below in Table 4.5 and Table 4.6

#### 4.2.1 Static analysis

Table 4.5 Static analysis parameters

| | |
|---|---|
| Code | IS 1893 (part 1)-2002 |
| Zone | IV |
| Zone factor | 0.24 |
| Response Reduction Factor | 5 |
| Importance factor | 1 |

#### 4.2.2 Response Spectrum analysis

Table 4.6 Response spectrum analysis parameters

| | |
|---|---|
| Damping ratio | 0.05 |
| Scale Factor | 1000 |
| Modal Combination Method | CQC |
| Directional Computation Type | SRSS |

### 4.3 Wind Loading Parameters

Table 4.7 Static wind analysis parameters

| | |
|---|---|
| Code | For towers: IS 875 (part 3)-1987<br>For sky bridge: IRC:6-2014 |
| Structure Class | C |
| Terrain category | 3 |
| $k_1$ | 1 |
| $k_3$ | 1 |
| Basic Wind speed | 47m/s |

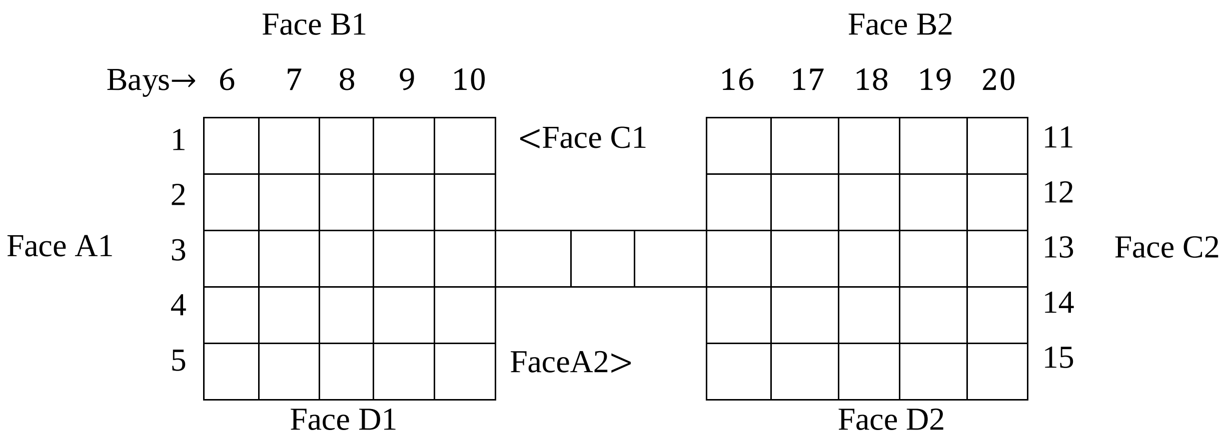



Figure 4.3 Outline of model plan for pressure coefficients

### 4.3.1 Wind Pressure Coefficients for Interfering Building

Table 4.8 Wind Pressure Coefficients for Interfering Building (Verma 2014)

| Face | Bay | External Pressure Coefficients | | | | | |
|---|---|---|---|---|---|---|---|
| | | Roof-Story 17 | | Stories 16-9 | | Story 8-GL | |
| | | Wx | Wy | Wx | Wy | Wx | Wy |
| A1 | 1-2 | 0.80 | -0.97 | 0.80 | -0.92 | 0.68 | -0.84 |
| | 3 | 1.00 | -0.90 | 1.00 | -0.83 | 0.90 | -0.77 |
| | 4-5 | 0.80 | -0.90 | 0.80 | -0.75 | 0.68 | -0.77 |
| B1 | 6-7 | -0.80 | -0.90 | -0.68 | -0.66 | -0.68 | -0.70 |
| | 8 | -0.85 | -0.88 | -0.76 | -0.66 | -0.70 | -0.70 |
| | 9-10 | -0.90 | -0.84 | -0.83 | -0.70 | -0.54 | -0.75 |
| C1 | 1-2 | -0.83 | -0.99 | -0.64 | -0.90 | -0.67 | -0.82 |
| | 3 | -0.83 | -0.91 | -0.64 | -0.80 | -0.67 | -0.79 |
| | 4-5 | -0.83 | -0.86 | -0.64 | -0.80 | -0.67 | -0.76 |
| D1 | 6-7 | -0.88 | 0.86 | -0.72 | 0.80 | -0.69 | 0.70 |
| | 8 | -0.88 | 1.00 | -0.72 | 1.00 | -0.75 | 0.94 |
| | 9-10 | -0.88 | 0.86 | -0.79 | 0.80 | -0.75 | 0.70 |

### 4.3.2 Wind Pressure Coefficients for Principal Building

Table 4.9 Wind Pressure Coefficients for Principal Building (Kheyari and Dalui 2015)

| Face | Bay | External Pressure Coefficients | | | | | |
|---|---|---|---|---|---|---|---|
| | | Roof-Story 17 | | Stories 16-9 | | Story 8-GL | |
| | | Wx | Wy | Wx | Wy | Wx | Wy |
| A2 | 11-12 | -0.71 | -0.77 | -0.80 | -0.76 | -0.66 | -0.70 |
| | 13 | -0.71 | -0.83 | -0.57 | -1.15 | -0.63 | -0.80 |
| | 14-15 | -0.75 | -0.77 | -0.60 | -0.96 | -0.63 | -1.20 |
| B2 | 16-17 | -0.25 | -0.67 | -0.37 | -0.64 | -0.69 | -0.64 |
| | 18 | -0.31 | -0.70 | -0.46 | -0.59 | -0.65 | -0.62 |
| | 19-20 | -0.34 | -0.67 | -0.61 | -0.59 | 0.00 | -0.62 |
| C2 | 11-12 | -0.32 | -0.86 | -0.30 | -0.75 | -0.28 | -0.75 |
| | 13 | -0.30 | -0.82 | -0.34 | -0.68 | -0.24 | -0.68 |
| | 14-15 | -0.34 | -0.82 | -0.34 | -0.68 | -0.28 | -0.65 |
| D2 | 16-17 | -0.28 | 0.92 | -0.38 | 0.92 | -0.25 | 0.85 |
| | 18 | -0.30 | 1.05 | -0.41 | 1.05 | -0.46 | 0.95 |
| | 19-20 | -0.44 | 0.78 | -0.56 | 0.78 | -0.60 | 0.65 |

### 4.3.3 Wind Pressure Coefficients of the structure with sky bridge

Table 4.10 Wind Pressure Coefficients of the structure with sky bridge (Verma 2014)

| Face | Bay | External Pressure Coefficients | | | | | |
|---|---|---|---|---|---|---|---|
| | | Roof-Story 17 | | Stories 16-9 | | Story 8-GL | |
| | | Wx | Wy | Wx | Wy | Wx | Wy |
| A1 | 1-2 | 0.80 | -0.88 | 0.80 | -0.93 | 0.68 | -0.80 |
| | 3 | 1.06 | -0.78 | 1.00 | -0.75 | 0.92 | -0.65 |
| | 4-5 | 0.80 | -0.78 | 0.80 | -0.71 | 0.70 | -0.74 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| B1 | 6-7 | -0.87 | -0.73 | -0.71 | -0.73 | -0.68 | -0.75 |
| | 8 | -0.81 | -0.65 | -0.67 | -0.65 | -0.64 | -0.70 |
| | 9-10 | -0.81 | -0.79 | -0.63 | -0.82 | -0.64 | -0.79 |
| C1 | 1<br>2 | -0.65 | -0.53<br>-0.25 | -0.59 | -0.45<br>-0.30 | -0.62 | -0.65 |
| | 3 | -0.62 | -0.14 | -0.61 | -0.20 | -0.62 | -0.90 |
| | 4<br>5 | -0.80 | -0.60<br>-1.44 | -0.63 | -0.50<br>-1.35 | -0.62 | -1.20 |
| D1 | 6-7 | -0.90 | 0.77 | -0.72 | 0.70 | -0.68 | 0.66 |
| | 8 | -0.80 | 1.04 | -0.67 | 1.02 | -0.63 | 0.94 |
| | 9-10 | -0.83 | 0.95 | -0.64 | 0.93 | -0.63 | 0.85 |
| A2 | 11<br>12 | -0.75 | -0.45<br>-0.30 | -0.80 | -0.30<br>-0.10 | -0.57 | -0.60 |
| | 13 | -0.67 | -0.17 | -0.57 | -0.01 | -0.65 | -0.41 |
| | 14<br>15 | -0.78 | -0.50<br>-1.17 | -0.69 | -0.20<br>-0.73 | -0.63 | -1.30 |
| B2 | 16-17 | -0.25 | -0.60 | -0.37 | -0.42 | -0.68 | -0.75 |
| | 18 | -0.31 | -0.55 | -0.46 | -0.45 | -0.69 | -0.82 |
| | 19-20 | -0.47 | -0.60 | -0.56 | -0.54 | 0.00 | -1.02 |
| C2 | 11-12 | -0.31 | -0.77 | -0.31 | -0.61 | -0.26 | -0.77 |
| | 13 | -0.30 | -0.67 | -0.25 | -0.56 | -0.21 | -0.67 |
| | 14-15 | -0.30 | -0.64 | -0.25 | -0.50 | -0.26 | -0.60 |
| D2 | 16-17 | -0.28 | 0.97 | -0.25 | 0.97 | -0.20 | 0.86 |
| | 18 | -0.34 | 1.07 | -0.41 | 1.07 | -0.40 | 0.92 |
| | 19-20 | -0.50 | 0.75 | -0.56 | 0.75 | -0.63 | 0.63 |

## 4.4 Results

### 4.4.1 Earthquake response

1. Maximum story drifts for load case Ex

Table 4.11 Drift for load case: Ex

| Story | Elevation (m) | Without Skybridge | With Skybridge |
|---|---|---|---|
| Roof | 78.6 | 0.000379 | 0.000376 |
| Story25 | 75.6 | 0.000422 | 0.000419 |
| Story24 | 72.6 | 0.000469 | 0.000465 |
| Story23 | 69.6 | 0.000521 | 0.000516 |
| Story22 | 66.6 | 0.000574 | 0.000563 |
| Story21 | 63.6 | 0.000626 | 0.000599 |
| Story20 | 60.6 | 0.000677 | 0.000643 |
| Story19 | 57.6 | 0.000724 | 0.000689 |
| Story18 | 54.6 | 0.000768 | 0.000732 |
| Story17 | 51.6 | 0.000807 | 0.000772 |
| Story16 | 48.6 | 0.000842 | 0.000807 |
| Story15 | 45.6 | 0.000872 | 0.000836 |
| Story14 | 42.6 | 0.000898 | 0.000859 |
| Story13 | 39.6 | 0.000918 | 0.000874 |
| Story12 | 36.6 | 0.000932 | 0.000884 |
| Story11 | 33.6 | 0.00094 | 0.000892 |
| Story10 | 30.6 | 0.000942 | 0.000895 |
| Story9 | 27.6 | 0.000937 | 0.00089 |
| Story8 | 24.6 | 0.000924 | 0.000877 |
| Story7 | 21.6 | 0.000901 | 0.000855 |
| Story6 | 18.6 | 0.000867 | 0.00082 |
| Story5 | 15.6 | 0.000817 | 0.00077 |
| Story4 | 12.6 | 0.000747 | 0.000701 |
| Story3 | 9.6 | 0.000651 | 0.000604 |
| Story2 | 6.6 | 0.000517 | 0.000472 |
| Story1 | 3.6 | 0.000311 | 0.000279 |
| Plinth Level | 0.6 | 0.000076 | 0.000069 |
| Base | 0 | 0 | 0 |

2. Maximum Story Drift for load case Ey

Table 4.12 Drift for load case: Ey

| Story | Elevation (m) | Without Skybridge | With Skybridge |
|---|---|---|---|
| Roof | 78.6 | 0.000383 | 0.000387 |
| Story25 | 75.6 | 0.000433 | 0.000437 |
| Story24 | 72.6 | 0.000487 | 0.00049 |
| Story23 | 69.6 | 0.000544 | 0.000546 |
| Story22 | 66.6 | 0.0006 | 0.000598 |
| Story21 | 63.6 | 0.000655 | 0.000638 |
| Story20 | 60.6 | 0.000707 | 0.000683 |
| Story19 | 57.6 | 0.000755 | 0.00073 |
| Story18 | 54.6 | 0.000799 | 0.000773 |
| Story17 | 51.6 | 0.000838 | 0.000813 |
| Story16 | 48.6 | 0.000872 | 0.000847 |
| Story15 | 45.6 | 0.000901 | 0.000876 |
| Story14 | 42.6 | 0.000925 | 0.000899 |
| Story13 | 39.6 | 0.000945 | 0.000913 |
| Story12 | 36.6 | 0.000959 | 0.000924 |
| Story11 | 33.6 | 0.000968 | 0.000932 |
| Story10 | 30.6 | 0.00097 | 0.000934 |
| Story9 | 27.6 | 0.000965 | 0.00093 |
| Story8 | 24.6 | 0.000955 | 0.00092 |
| Story7 | 21.6 | 0.000937 | 0.000901 |
| Story6 | 18.6 | 0.000909 | 0.000872 |
| Story5 | 15.6 | 0.000866 | 0.000827 |
| Story4 | 12.6 | 0.000804 | 0.000764 |
| Story3 | 9.6 | 0.000715 | 0.000671 |
| Story2 | 6.6 | 0.000583 | 0.000539 |
| Story1 | 3.6 | 0.000365 | 0.000332 |
| Plinth Level | 0.6 | 0.000089 | 0.000081 |
| Base | 0 | 0 | 0 |

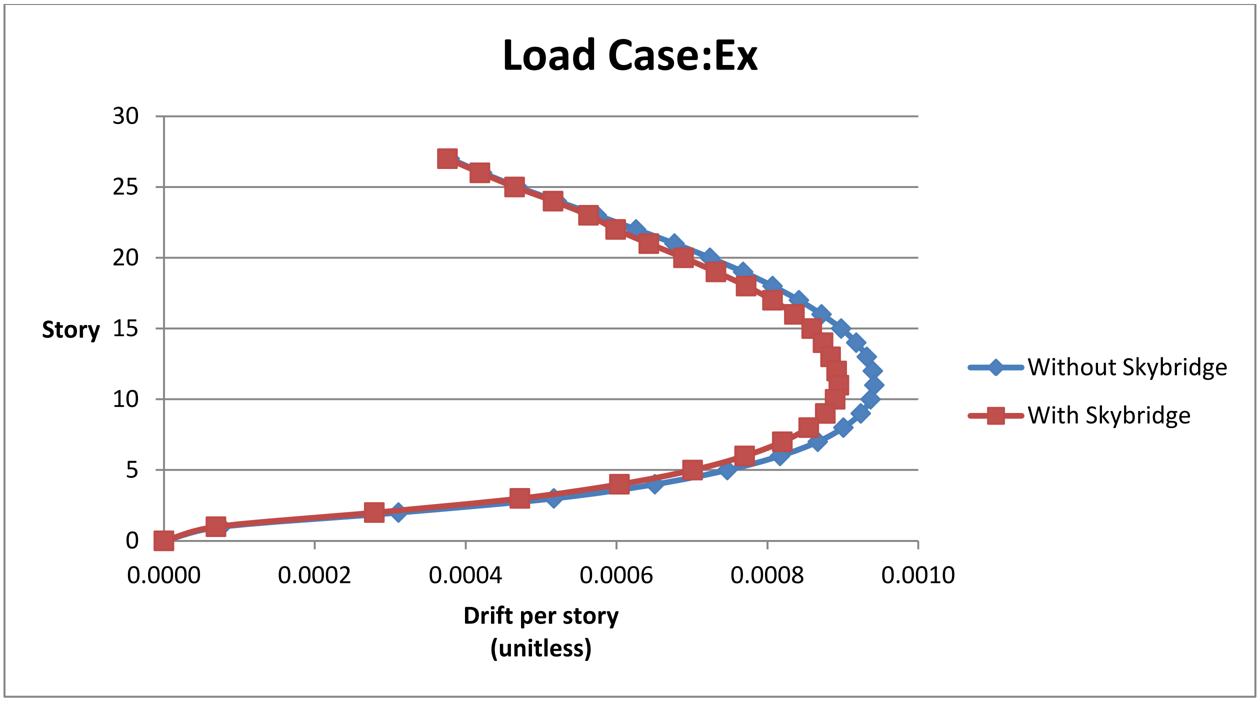



Figure 4.4 Graphical Representation of drift for load case: Ex

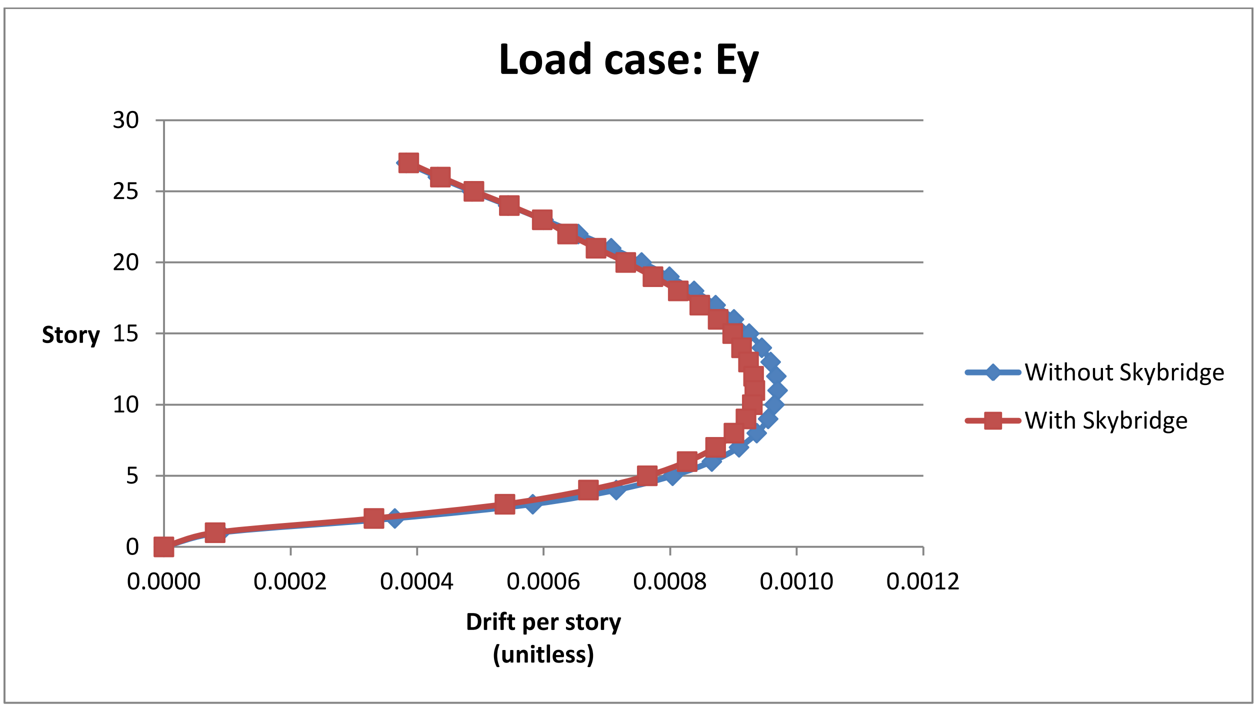



Figure 4.5 Graphical Representation of drift for load case: Ey

3. Maximum Story Drift for Response Spectrum Load case

Table 4.13 Drift for load case: Response Spectrum

| Story | Elevation (m) | Without Skybridge | | With Skybridge | |
|---|---|---|---|---|---|
| | | X | Y | X | Y |
| Roof | 78.6 | 0.000284 | 0.000282 | 0.000282 | 0.000285 |
| Story25 | 75.6 | 0.000322 | 0.000326 | 0.00032 | 0.000329 |
| Story24 | 72.6 | 0.000359 | 0.000369 | 0.000357 | 0.000372 |
| Story23 | 69.6 | 0.000395 | 0.00041 | 0.000392 | 0.000412 |
| Story22 | 66.6 | 0.000429 | 0.000447 | 0.000419 | 0.000444 |
| Story21 | 63.6 | 0.00046 | 0.000479 | 0.000434 | 0.000464 |
| Story20 | 60.6 | 0.000487 | 0.000508 | 0.000458 | 0.000491 |
| Story19 | 57.6 | 0.000513 | 0.000533 | 0.000483 | 0.000516 |
| Story18 | 54.6 | 0.000536 | 0.000556 | 0.000507 | 0.00054 |
| Story17 | 51.6 | 0.000558 | 0.000577 | 0.000528 | 0.000561 |
| Story16 | 48.6 | 0.000578 | 0.000597 | 0.000548 | 0.000581 |
| Story15 | 45.6 | 0.000596 | 0.000615 | 0.000567 | 0.000599 |
| Story14 | 42.6 | 0.000614 | 0.000632 | 0.000583 | 0.000616 |
| Story13 | 39.6 | 0.000629 | 0.000647 | 0.000595 | 0.00063 |
| Story12 | 36.6 | 0.000643 | 0.00066 | 0.000602 | 0.000639 |
| Story11 | 33.6 | 0.000654 | 0.000672 | 0.000611 | 0.000648 |
| Story10 | 30.6 | 0.000663 | 0.00068 | 0.00062 | 0.000656 |
| Story9 | 27.6 | 0.000668 | 0.000686 | 0.000625 | 0.000661 |
| Story8 | 24.6 | 0.00067 | 0.00069 | 0.000627 | 0.000665 |
| Story7 | 21.6 | 0.000666 | 0.000691 | 0.000624 | 0.000664 |
| Story6 | 18.6 | 0.000655 | 0.000685 | 0.000613 | 0.000656 |
| Story5 | 15.6 | 0.000633 | 0.00067 | 0.00059 | 0.00064 |
| Story4 | 12.6 | 0.000595 | 0.000639 | 0.000552 | 0.000607 |
| Story3 | 9.6 | 0.000533 | 0.000584 | 0.00049 | 0.00055 |
| Story2 | 6.6 | 0.000436 | 0.00049 | 0.000395 | 0.000455 |
| Story1 | 3.6 | 0.000271 | 0.000316 | 0.000242 | 0.00029 |
| Plinth Level | 0.6 | 0.000068 | 0.000079 | 0.000061 | 0.000073 |
| Base | 0 | 0 | 0 | 0 | 0 |

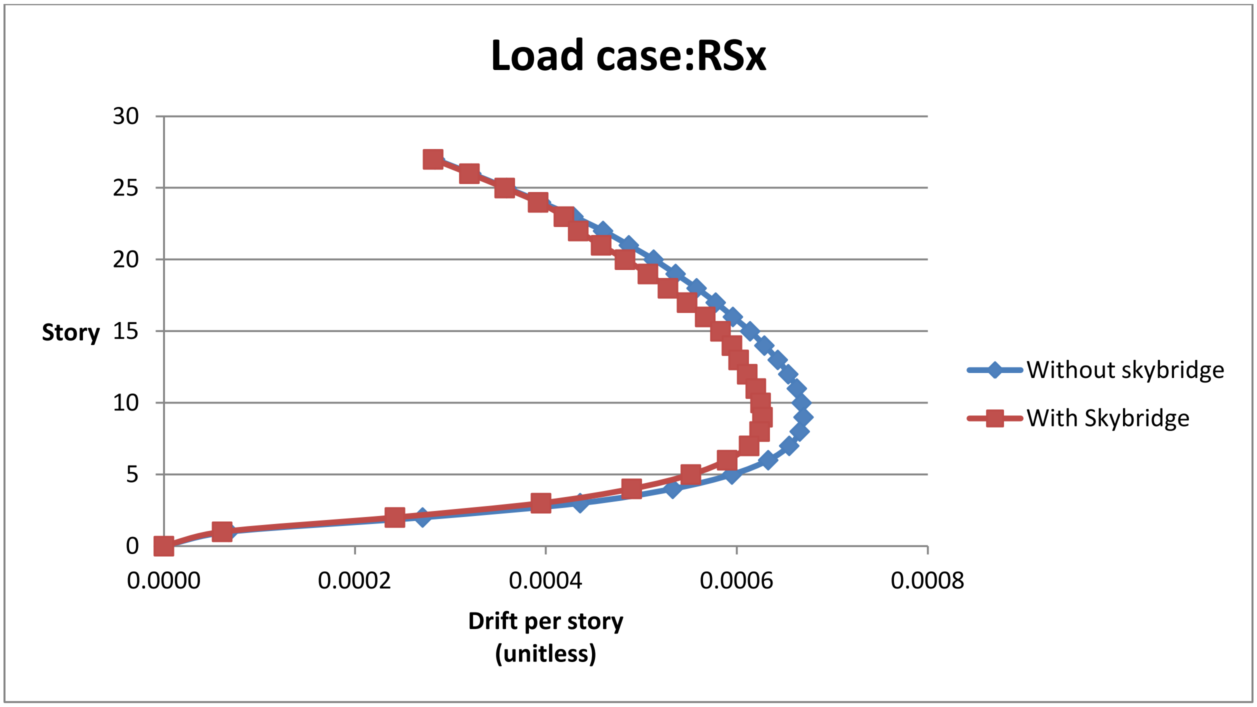



Figure 4.6 Graphical Representation of drift for load case: RSx

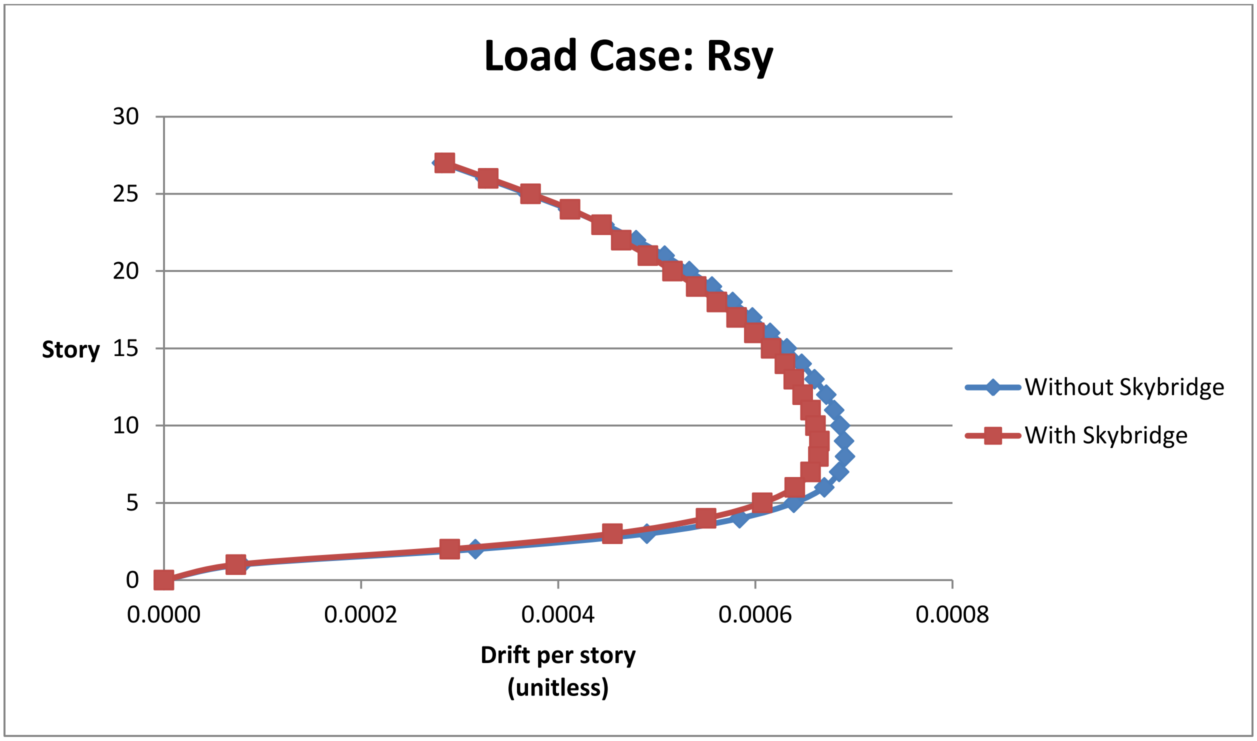



Figure 4.7 Graphical Representation of drift for load case: RSy

4. Maximum Story Drift For load combination: 1.5(DL+Ex)

Table 4.14 Drift for load combination: 1.5(DL+Ex)

| Story | Elevation (m) | Without Skybridge | With Skybridge |
|---|---|---|---|
| Roof | 78.6 | 0.000574 | 0.00059 |
| Story25 | 75.6 | 0.00064 | 0.000655 |
| Story24 | 72.6 | 0.00071 | 0.000723 |
| Story23 | 69.6 | 0.000788 | 0.000796 |
| Story22 | 66.6 | 0.000868 | 0.000865 |
| Story21 | 63.6 | 0.000946 | 0.000901 |
| Story20 | 60.6 | 0.001022 | 0.000973 |
| Story19 | 57.6 | 0.001093 | 0.001036 |
| Story18 | 54.6 | 0.001158 | 0.001102 |
| Story17 | 51.6 | 0.001218 | 0.001162 |
| Story16 | 48.6 | 0.00127 | 0.001215 |
| Story15 | 45.6 | 0.001315 | 0.001259 |
| Story14 | 42.6 | 0.001353 | 0.001293 |
| Story13 | 39.6 | 0.001382 | 0.001313 |
| Story12 | 36.6 | 0.001404 | 0.001338 |
| Story11 | 33.6 | 0.001416 | 0.001345 |
| Story10 | 30.6 | 0.001419 | 0.001347 |
| Story9 | 27.6 | 0.001411 | 0.001339 |
| Story8 | 24.6 | 0.001391 | 0.001318 |
| Story7 | 21.6 | 0.001357 | 0.001285 |
| Story6 | 18.6 | 0.001305 | 0.001233 |
| Story5 | 15.6 | 0.001229 | 0.001159 |
| Story4 | 12.6 | 0.001124 | 0.001054 |
| Story3 | 9.6 | 0.000979 | 0.00091 |
| Story2 | 6.6 | 0.000777 | 0.000711 |
| Story1 | 3.6 | 0.000468 | 0.000421 |
| Plinth Level | 0.6 | 0.000114 | 0.000104 |
| Base | 0 | 0 | 0 |

5. Maximum Story Drift for load combination: 1.5(DL-Ey)

Table 4.15 Drift for load combination: 1.5(DL-Ey)

| Story | Elevation (m) | Without Skybridge | With Skybridge |
|---|---|---|---|
| Roof | 78.6 | 0.000583 | 0.000589 |
| Story25 | 75.6 | 0.000658 | 0.000664 |
| Story24 | 72.6 | 0.000739 | 0.000744 |
| Story23 | 69.6 | 0.000824 | 0.000828 |
| Story22 | 66.6 | 0.000909 | 0.000904 |
| Story21 | 63.6 | 0.000991 | 0.000962 |
| Story20 | 60.6 | 0.001069 | 0.00103 |
| Story19 | 57.6 | 0.001141 | 0.0011 |
| Story18 | 54.6 | 0.001206 | 0.001166 |
| Story17 | 51.6 | 0.001264 | 0.001225 |
| Story16 | 48.6 | 0.001315 | 0.001276 |
| Story15 | 45.6 | 0.001359 | 0.00132 |
| Story14 | 42.6 | 0.001395 | 0.001354 |
| Story13 | 39.6 | 0.001424 | 0.001375 |
| Story12 | 36.6 | 0.001445 | 0.001392 |
| Story11 | 33.6 | 0.001458 | 0.001403 |
| Story10 | 30.6 | 0.001461 | 0.001406 |
| Story9 | 27.6 | 0.001454 | 0.0014 |
| Story8 | 24.6 | 0.001439 | 0.001384 |
| Story7 | 21.6 | 0.001411 | 0.001356 |
| Story6 | 18.6 | 0.001368 | 0.001311 |
| Story5 | 15.6 | 0.001304 | 0.001244 |
| Story4 | 12.6 | 0.00121 | 0.001148 |
| Story3 | 9.6 | 0.001075 | 0.001009 |
| Story2 | 6.6 | 0.000877 | 0.000809 |
| Story1 | 3.6 | 0.000549 | 0.000497 |
| Plinth Level | 0.6 | 0.000133 | 0.000122 |
| Base | 0 | 0 | 0 |

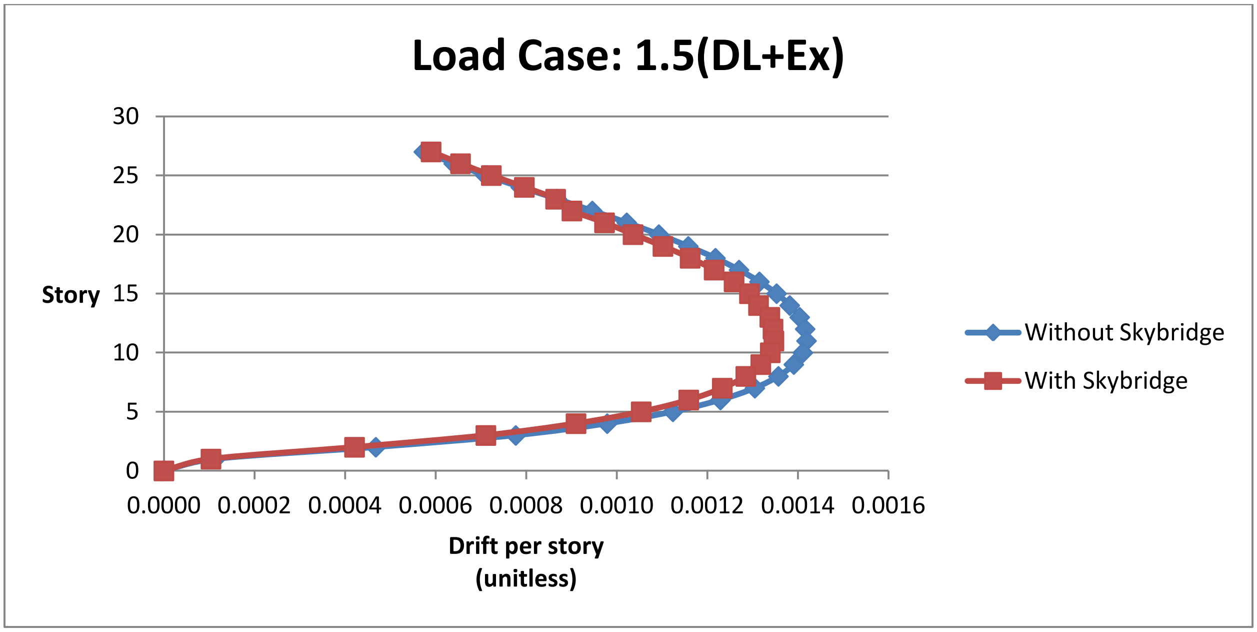



Figure 4.8 Graphical Representation of drift for load combination: 1.5(DL+Ex)

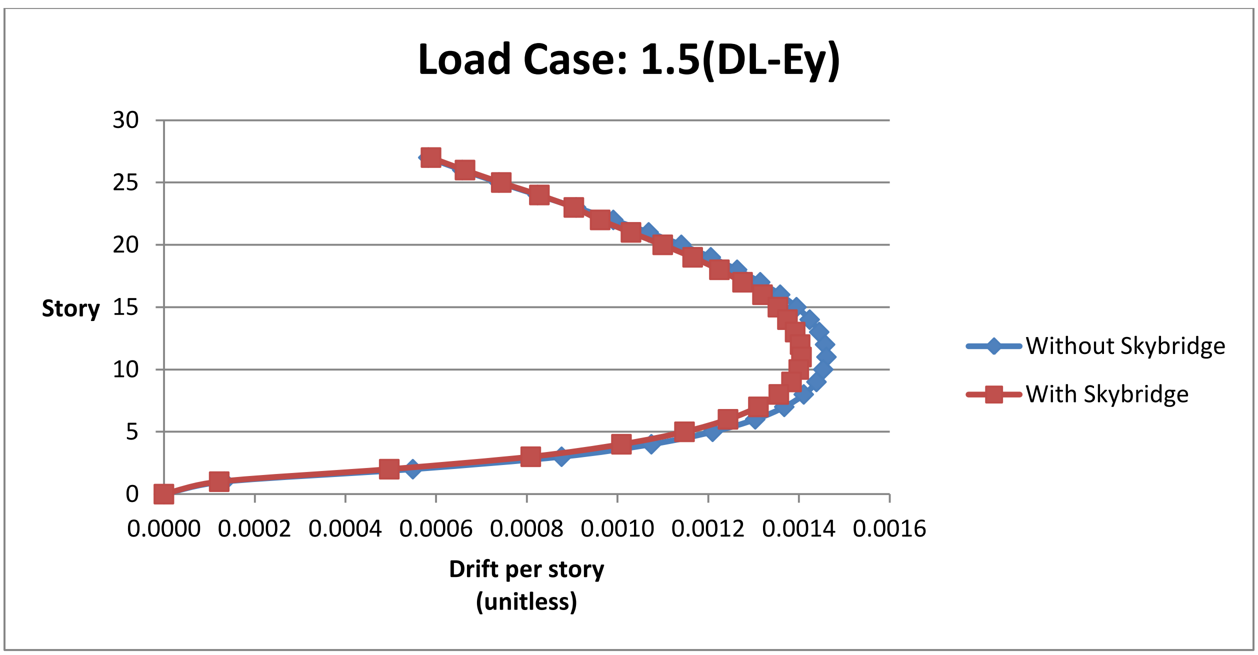



Figure 4.9 Graphical Representation of drift for load combination: 1.5(DL-Ey)

6. Maximum Story Displacements for load case Ex

Table 4.16 Displacement for load case: Ex

| Story | Elevation | Without Skybridge | With Skybridge |
|---|---|---|---|
| | m | mm | mm |
| Roof | 78.6 | 56.998 | 54.315 |
| Story25 | 75.6 | 55.862 | 53.188 |
| Story24 | 72.6 | 54.596 | 51.931 |
| Story23 | 69.6 | 53.19 | 50.535 |
| Story22 | 66.6 | 51.628 | 48.988 |
| Story21 | 63.6 | 49.907 | 47.299 |
| Story20 | 60.6 | 48.028 | 45.501 |
| Story19 | 57.6 | 45.997 | 43.572 |
| Story18 | 54.6 | 43.825 | 41.505 |
| Story17 | 51.6 | 41.521 | 39.309 |
| Story16 | 48.6 | 39.099 | 36.993 |
| Story15 | 45.6 | 36.572 | 34.573 |
| Story14 | 42.6 | 33.954 | 32.064 |
| Story13 | 39.6 | 31.262 | 29.486 |
| Story12 | 36.6 | 28.509 | 26.865 |
| Story11 | 33.6 | 25.713 | 24.211 |
| Story10 | 30.6 | 22.892 | 21.535 |
| Story9 | 27.6 | 20.064 | 18.851 |
| Story8 | 24.6 | 17.253 | 16.181 |
| Story7 | 21.6 | 14.481 | 13.549 |
| Story6 | 18.6 | 11.777 | 10.984 |
| Story5 | 15.6 | 9.176 | 8.523 |
| Story4 | 12.6 | 6.724 | 6.212 |
| Story3 | 9.6 | 4.482 | 4.11 |
| Story2 | 6.6 | 2.53 | 2.297 |
| Story1 | 3.6 | 0.98 | 0.88 |
| Plinth level | 0.6 | 0.046 | 0.041 |
| Base | 0 | 0 | 0 |

7. Maximum Story Displacements for load case Ey

Table 4.17 Displacement for load case: Ey

| Story | Elevation | Without Skybridge | With Skybridge |
|---|---|---|---|
| | m | mm | mm |
| Roof | 78.6 | 59.58 | 57.569 |
| Story25 | 75.6 | 58.43 | 56.409 |
| Story24 | 72.6 | 57.129 | 55.099 |
| Story23 | 69.6 | 55.668 | 53.629 |
| Story22 | 66.6 | 54.037 | 51.992 |
| Story21 | 63.6 | 52.236 | 50.199 |
| Story20 | 60.6 | 50.27 | 48.287 |
| Story19 | 57.6 | 48.148 | 46.238 |
| Story18 | 54.6 | 45.883 | 44.049 |
| Story17 | 51.6 | 43.487 | 41.729 |
| Story16 | 48.6 | 40.974 | 39.291 |
| Story15 | 45.6 | 38.358 | 36.75 |
| Story14 | 42.6 | 35.655 | 34.121 |
| Story13 | 39.6 | 32.879 | 31.423 |
| Story12 | 36.6 | 30.045 | 28.683 |
| Story11 | 33.6 | 27.168 | 25.911 |
| Story10 | 30.6 | 24.264 | 23.116 |
| Story9 | 27.6 | 21.355 | 20.315 |
| Story8 | 24.6 | 18.459 | 17.526 |
| Story7 | 21.6 | 15.593 | 14.766 |
| Story6 | 18.6 | 12.78 | 12.063 |
| Story5 | 15.6 | 10.054 | 9.448 |
| Story4 | 12.6 | 7.455 | 6.966 |
| Story3 | 9.6 | 5.042 | 4.675 |
| Story2 | 6.6 | 2.898 | 2.661 |
| Story1 | 3.6 | 1.149 | 1.044 |
| Plinth level | 0.6 | 0.053 | 0.049 |
| Base | 0 | 0 | 0 |

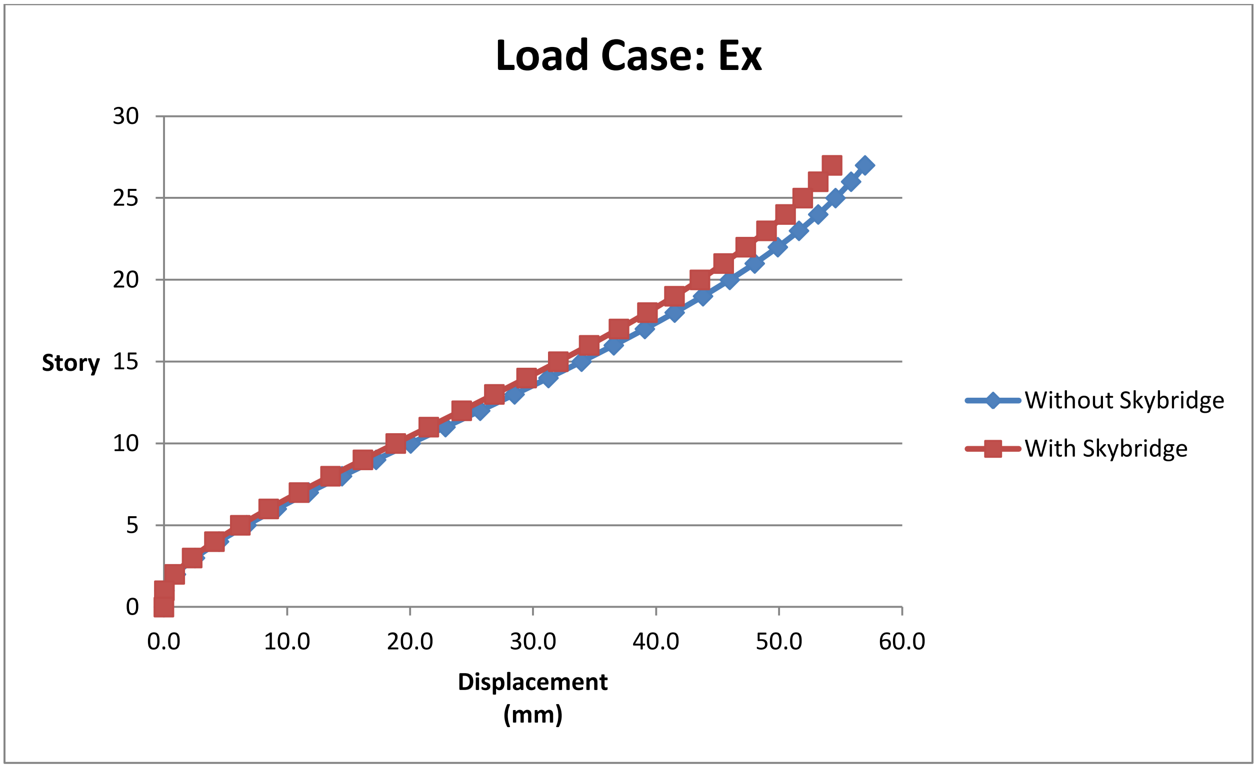



Figure 4.10 Graphical Representation of displacement for load case: Ex

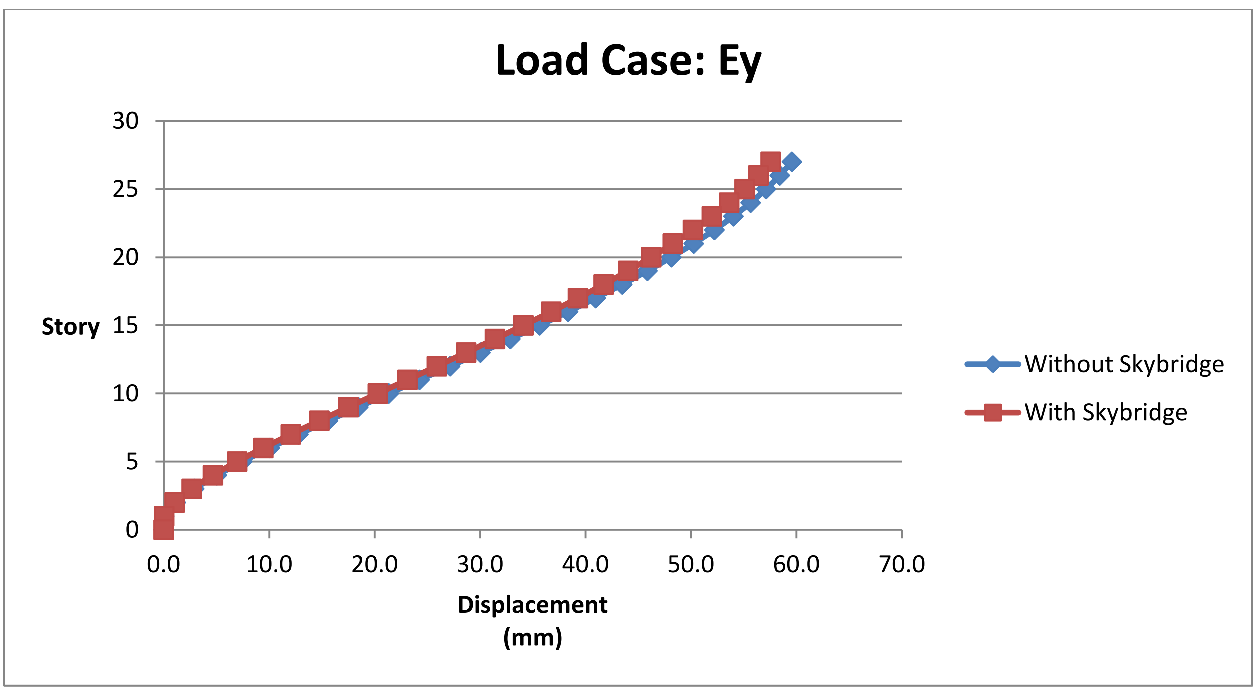



Figure 4.11 Graphical Representation of displacement for load case: Ey

8. Maximum Story Displacement For Response Spectrum Load Case

Table 4.18: Displacement for load case: Response Spectrum

| Story | Elevation (m) | Without Skybridge | | With Skybridge | |
|---|---|---|---|---|---|
| | | X | Y | X | Y |
| Roof | 78.6 | 38.588 | 40.23 | 36.239 | 38.807 |
| Story25 | 75.6 | 37.862 | 39.491 | 35.519 | 38.061 |
| Story24 | 72.6 | 37.055 | 38.658 | 34.718 | 37.222 |
| Story23 | 69.6 | 36.164 | 37.73 | 33.834 | 36.288 |
| Story22 | 66.6 | 35.183 | 36.704 | 32.865 | 35.26 |
| Story21 | 63.6 | 34.113 | 35.583 | 31.823 | 34.149 |
| Story20 | 60.6 | 32.954 | 34.371 | 30.74 | 32.983 |
| Story19 | 57.6 | 31.709 | 33.073 | 29.582 | 31.734 |
| Story18 | 54.6 | 30.381 | 31.692 | 28.341 | 30.401 |
| Story17 | 51.6 | 28.972 | 30.234 | 27.02 | 28.988 |
| Story16 | 48.6 | 27.486 | 28.699 | 25.622 | 27.5 |
| Story15 | 45.6 | 25.926 | 27.094 | 24.15 | 25.94 |
| Story14 | 42.6 | 24.295 | 25.42 | 22.608 | 24.311 |
| Story13 | 39.6 | 22.596 | 23.682 | 21.002 | 22.618 |
| Story12 | 36.6 | 20.836 | 21.883 | 19.345 | 20.872 |
| Story11 | 33.6 | 19.018 | 20.028 | 17.649 | 19.081 |
| Story10 | 30.6 | 17.15 | 18.122 | 15.909 | 17.247 |
| Story9 | 27.6 | 15.238 | 16.174 | 14.126 | 15.372 |
| Story8 | 24.6 | 13.295 | 14.189 | 12.31 | 13.463 |
| Story7 | 21.6 | 11.331 | 12.175 | 10.474 | 11.528 |
| Story6 | 18.6 | 9.364 | 10.143 | 8.635 | 9.579 |
| Story5 | 15.6 | 7.42 | 8.115 | 6.819 | 7.638 |
| Story4 | 12.6 | 5.533 | 6.121 | 5.061 | 5.736 |
| Story3 | 9.6 | 3.756 | 4.213 | 3.413 | 3.924 |
| Story2 | 6.6 | 2.162 | 2.465 | 1.947 | 2.278 |
| Story1 | 3.6 | 0.855 | 0.996 | 0.763 | 0.913 |
| Plinth Level | 0.6 | 0.041 | 0.047 | 0.037 | 0.044 |
| Base | 0 | 0 | 0 | 0 | 0 |

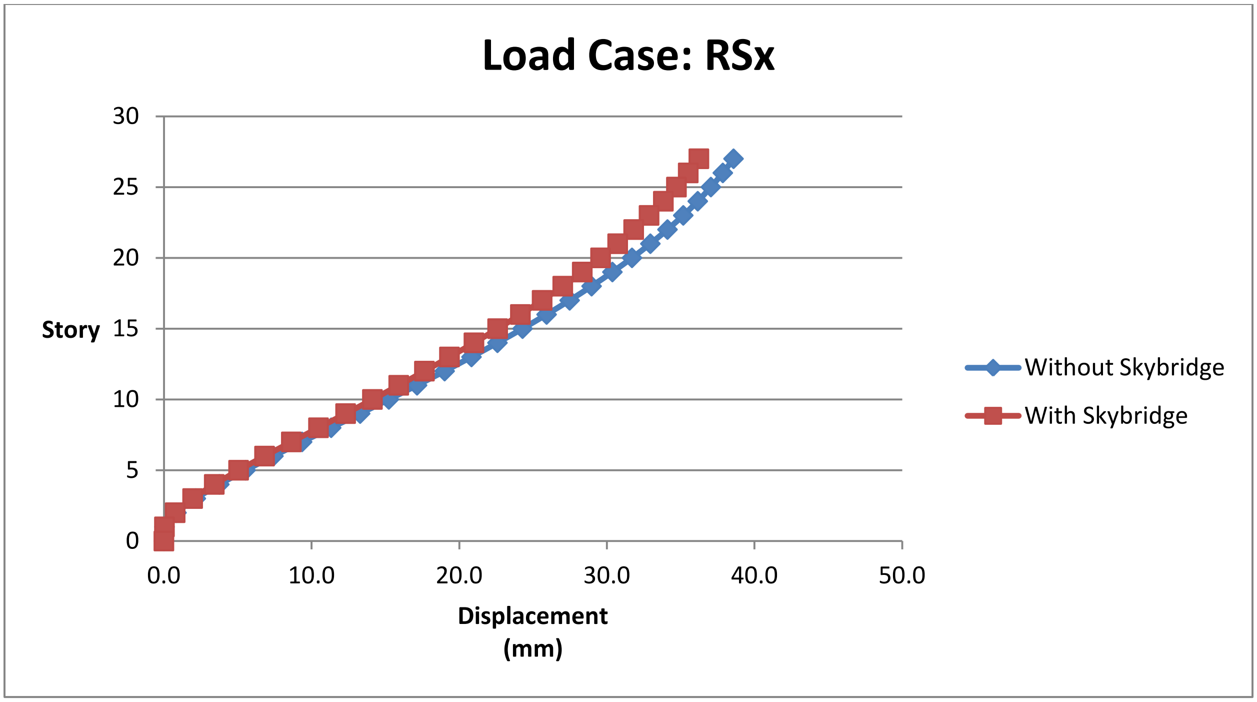



Figure 4.12 Graphical Representation of displacement for load case: RSx

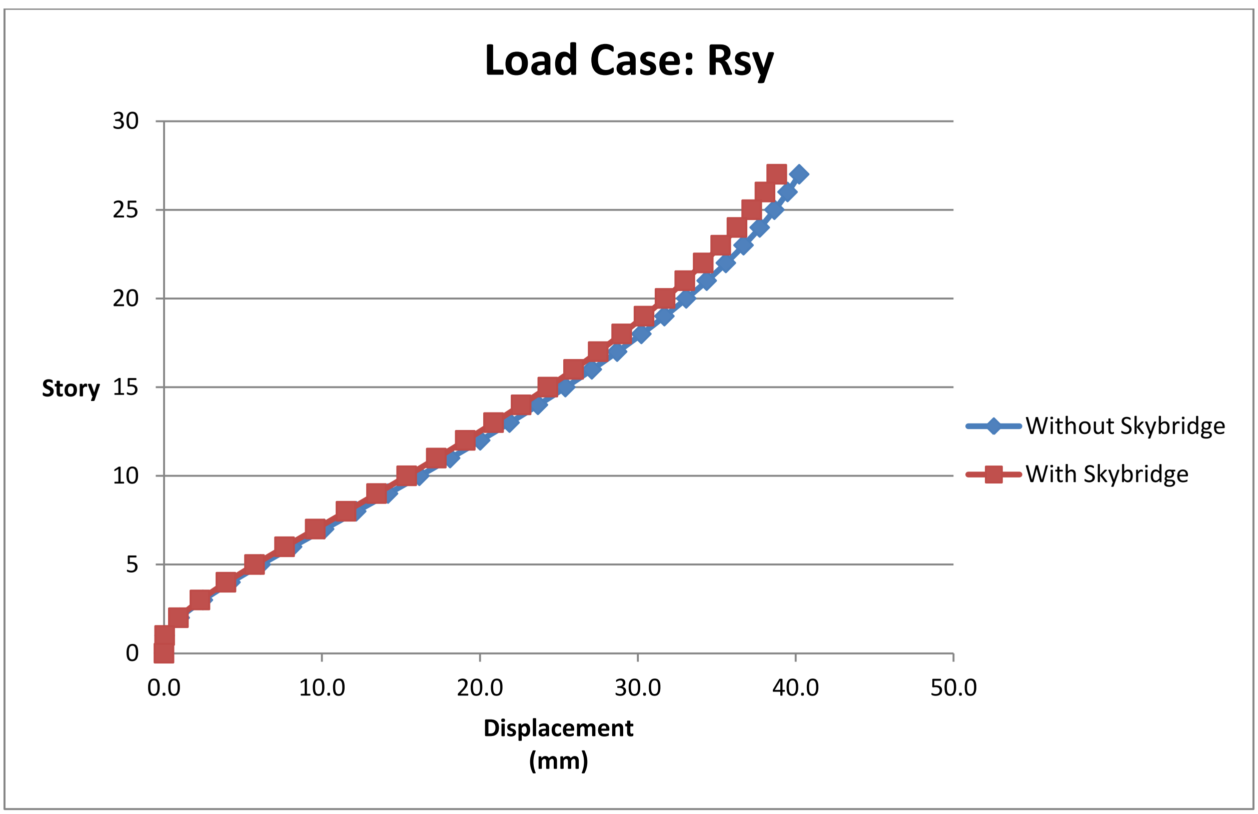



Figure 4.13 Graphical Representation of displacement for load case: RSy

9. Maximum Displacement for load combination 1.5(DL+Ex)

Table 4.19 Displacement for load combination: 1.5(DL+Ex)

| Story | Elevation | Without Skybridge | With Skybridge |
|---|---|---|---|
| | m | mm | mm |
| Roof | 78.6 | 85.921 | 81.942 |
| Story25 | 75.6 | 84.198 | 80.171 |
| Story24 | 72.6 | 82.277 | 78.206 |
| Story23 | 69.6 | 80.147 | 76.036 |
| Story22 | 66.6 | 77.783 | 73.647 |
| Story21 | 63.6 | 75.181 | 71.051 |
| Story20 | 60.6 | 72.342 | 68.347 |
| Story19 | 57.6 | 69.276 | 65.468 |
| Story18 | 54.6 | 65.997 | 62.361 |
| Story17 | 51.6 | 62.521 | 59.054 |
| Story16 | 48.6 | 58.868 | 55.567 |
| Story15 | 45.6 | 55.059 | 51.923 |
| Story14 | 42.6 | 51.114 | 48.159 |
| Story13 | 39.6 | 47.057 | 44.28 |
| Story12 | 36.6 | 42.91 | 40.342 |
| Story11 | 33.6 | 38.699 | 36.381 |
| Story10 | 30.6 | 34.45 | 32.367 |
| Story9 | 27.6 | 30.192 | 28.342 |
| Story8 | 24.6 | 25.959 | 24.335 |
| Story7 | 21.6 | 21.787 | 20.383 |
| Story6 | 18.6 | 17.716 | 16.529 |
| Story5 | 15.6 | 13.803 | 12.829 |
| Story4 | 12.6 | 10.115 | 9.352 |
| Story3 | 9.6 | 6.742 | 6.188 |
| Story2 | 6.6 | 3.805 | 3.459 |
| Story1 | 3.6 | 1.474 | 1.325 |
| Plinth level | 0.6 | 0.068 | 0.062 |
| Base | 0 | 0 | 0 |

10. Maximum Displacements for load combination 1.5(DL-Ey)

Table 4.20 Displacement for load combination: 1.5(DL-Ey)

| Story | Elevation | Without Skybridge | With Skybridge |
|---|---|---|---|
| | m | mm | mm |
| Roof | 78.6 | 89.863 | 86.754 |
| Story25 | 75.6 | 88.115 | 84.988 |
| Story24 | 72.6 | 86.139 | 82.996 |
| Story23 | 69.6 | 83.924 | 80.764 |
| Story22 | 66.6 | 81.453 | 78.281 |
| Story21 | 63.6 | 78.727 | 75.568 |
| Story20 | 60.6 | 75.753 | 72.683 |
| Story19 | 57.6 | 72.547 | 69.593 |
| Story18 | 54.6 | 69.126 | 66.293 |
| Story17 | 51.6 | 65.508 | 62.795 |
| Story16 | 48.6 | 61.716 | 59.121 |
| Story15 | 45.6 | 57.771 | 55.293 |
| Story14 | 42.6 | 53.694 | 51.334 |
| Story13 | 39.6 | 49.509 | 47.271 |
| Story12 | 36.6 | 45.237 | 43.145 |
| Story11 | 33.6 | 40.901 | 38.97 |
| Story10 | 30.6 | 36.525 | 34.761 |
| Story9 | 27.6 | 32.143 | 30.543 |
| Story8 | 24.6 | 27.78 | 26.344 |
| Story7 | 21.6 | 23.464 | 22.191 |
| Story6 | 18.6 | 19.229 | 18.124 |
| Story5 | 15.6 | 15.125 | 14.191 |
| Story4 | 12.6 | 11.214 | 10.459 |
| Story3 | 9.6 | 7.583 | 7.016 |
| Story2 | 6.6 | 4.357 | 3.991 |
| Story1 | 3.6 | 1.726 | 1.564 |
| Plinth level | 0.6 | 0.08 | 0.073 |
| Base | 0 | 0 | 0 |

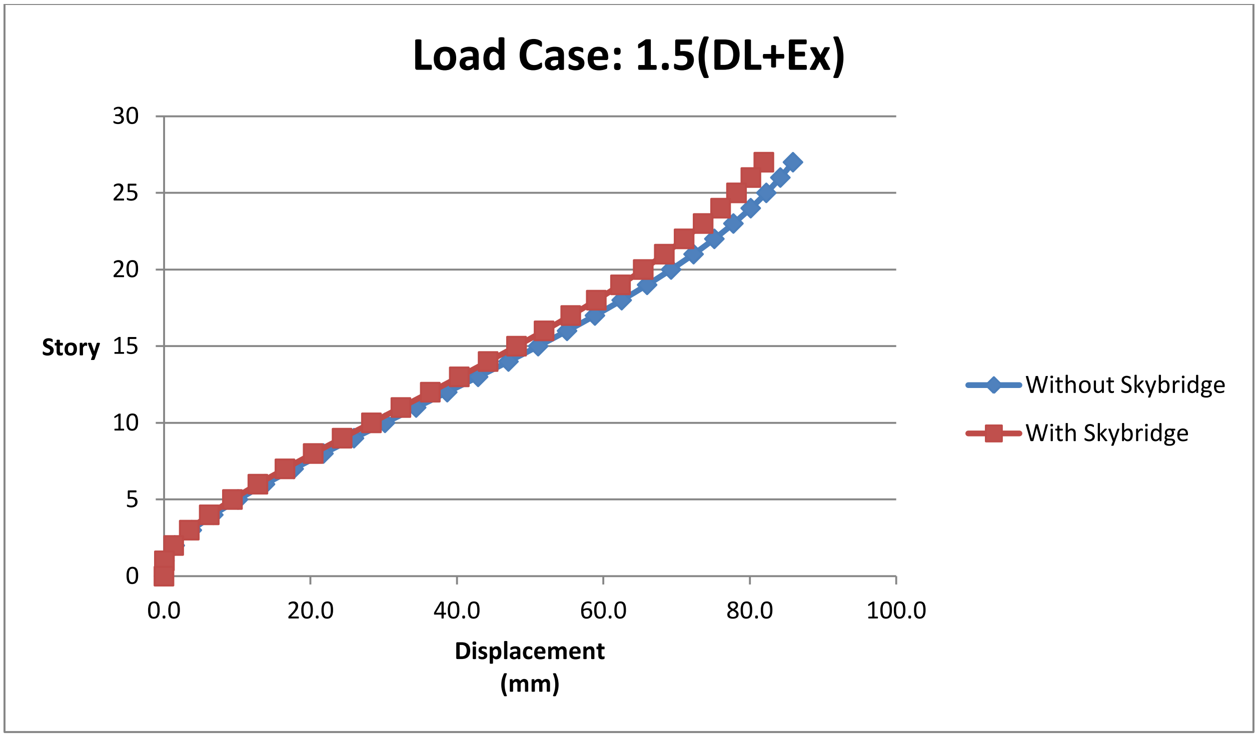



Figure 4.14 Graphical Representation of displacement for load combination:1.5(DL+Ex)

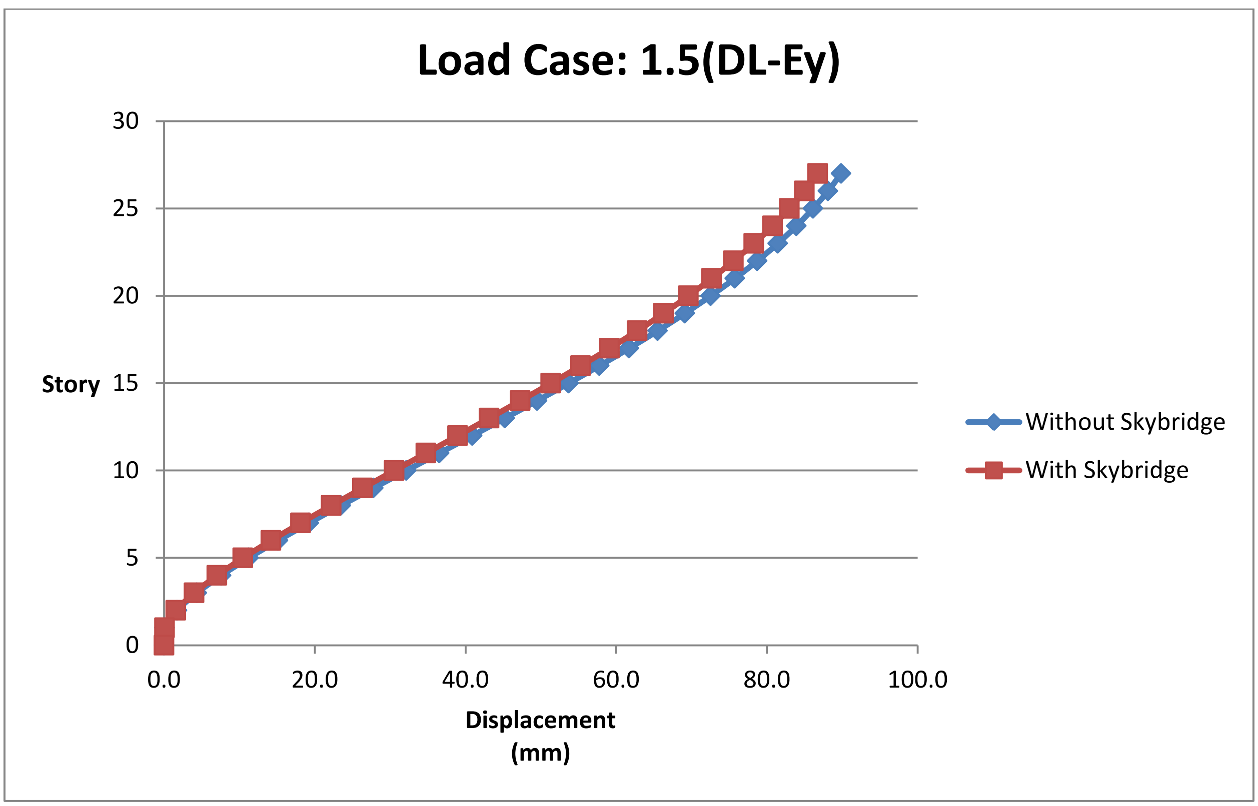



Figure 4.15 Graphical Representation of displacement for load combination: 1.5(DL-Ey)

11. Base Reactions

Table 4.21 Base Reactions as calculated by ETABS

| Load Case | | Fx (kN) | Fy (kN) | Fz (kN) | Mx (kNm) | My(kNm) | Mz(kNm) |
|---|---|---|---|---|---|---|---|
| Ex | M | -6978 | 0 | 0 | -70 | -435731 | 88355 |
| | N | -6975 | 0 | 0 | -77 | -437233 | 88234 |
| Ey | M | 0 | -6802 | 0 | 425719 | 66 | -243960 |
| | N | 0 | -6699 | 0 | 421000 | 71 | -240208 |
| 1.2(DL+LL+Ex) | M | -8374 | 0 | 875865 | 10072363 | -30740213 | 106031 |
| | N | -8370 | 0 | 878994 | 10108340 | -30852681 | 105882 |
| 1.2(DL+LL-Ex) | M | 8374 | 0 | 875865 | 10072531 | -29694459 | -106021 |
| | N | 8370 | 0 | 878994 | 10108524 | -29803322 | -105880 |
| 1.2(DL+LL+Ey) | M | 0 | -8163 | 875865 | 10583310 | -30217257 | -292748 |
| | N | 0 | -8039 | 878994 | 10613632 | -30327916 | -288249 |
| 1.2(DL+LL-Ey) | M | 0 | 8163 | 875865 | 9561584 | -30217415 | 292757 |
| | N | 0 | 8039 | 878994 | 9603233 | -30328086 | 288252 |
| 1.5(DL+Ex) | M | -10467.5 | 0 | 950300 | 10928347 | -33438946 | 132538 |
| | N | -10463 | 0 | 953563 | 10965866 | -33557176 | 132352 |
| 1.5(DL-Ex) | M | 10467.5 | 0 | 950300 | 10928556 | -32131754 | -132528 |
| | N | 10463 | 0 | 953563 | 10966096 | -32245476 | -132350 |
| 1.5(DL+Ey) | M | 0 | -10204 | 950300 | 11567030 | -32785252 | -365936 |
| | N | 0 | -10049 | 953563 | 11597480 | -32901220 | -360312 |
| 1.5(DL-Ey) | M | 0 | 10204 | 950300 | 10289873 | -32785449 | 365945 |
| | N | 0 | 10049 | 953563 | 10334482 | -32901433 | 360314 |
| $RS_{max}$ | M | 6368.5 | 6222 | 0 | 286685 | 291803 | 235114 |
| | N | 6369.2 | 6153 | 0 | 284052 | 293404 | 232727 |

Note: M indicates ‘without sky bridge’ results

N indicates ‘with sky bridge’ results

### 4.4.2 Wind response

1. Maximum Story drifts for load case: Wx

Table 4.22 Drift for load case: Wx

| Story | Elevation (m) | Interfering Building | Principal Building | With Skybridge |
|---|---|---|---|---|
| Roof | 78.6 | 0.00024 | 0.000059 | 0.000095 |
| Story25 | 75.6 | 0.000257 | 0.000063 | 0.000108 |
| Story24 | 72.6 | 0.000274 | 0.000067 | 0.00012 |
| Story23 | 69.6 | 0.000295 | 0.000073 | 0.000131 |
| Story22 | 66.6 | 0.000319 | 0.000079 | 0.000135 |
| Story21 | 63.6 | 0.000344 | 0.000085 | 0.000113 |
| Story20 | 60.6 | 0.00037 | 0.000092 | 0.000134 |
| Story19 | 57.6 | 0.000397 | 0.000098 | 0.000145 |
| Story18 | 54.6 | 0.000424 | 0.000105 | 0.000151 |
| Story17 | 51.6 | 0.000449 | 0.000112 | 0.000157 |
| Story16 | 48.6 | 0.000474 | 0.000118 | 0.000174 |
| Story15 | 45.6 | 0.000496 | 0.000125 | 0.000188 |
| Story14 | 42.6 | 0.000517 | 0.00013 | 0.000198 |
| Story13 | 39.6 | 0.000536 | 0.000135 | 0.000196 |
| Story12 | 36.6 | 0.000551 | 0.00014 | 0.000237 |
| Story11 | 33.6 | 0.000563 | 0.000144 | 0.000251 |
| Story10 | 30.6 | 0.00057 | 0.000147 | 0.000253 |
| Story9 | 27.6 | 0.000571 | 0.00015 | 0.000249 |
| Story8 | 24.6 | 0.000565 | 0.000154 | 0.000239 |
| Story7 | 21.6 | 0.000552 | 0.000156 | 0.000225 |
| Story6 | 18.6 | 0.000529 | 0.000155 | 0.000227 |
| Story5 | 15.6 | 0.000495 | 0.000152 | 0.000225 |
| Story4 | 12.6 | 0.000447 | 0.000145 | 0.000216 |
| Story3 | 9.6 | 0.000383 | 0.000133 | 0.000196 |
| Story2 | 6.6 | 0.000299 | 0.000114 | 0.000161 |
| Story1 | 3.6 | 0.000183 | 0.000076 | 0.000101 |
| Plinth Level | 0.6 | 0.000051 | 0.00002 | 0.000027 |
| Base | 0 | 0 | 0 | 0 |

2. Maximum Story Drifts for load case: Wy

Table 4.23 Drift for load case: Wy

| Story | Elevation (m) | Interfering Building | Principal Building | With Skybridge |
|---|---|---|---|---|
| Roof | 78.6 | 0.000285 | 0.000258 | 0.000255 |
| Story25 | 75.6 | 0.00031 | 0.000281 | 0.000284 |
| Story24 | 72.6 | 0.000338 | 0.000305 | 0.000316 |
| Story23 | 69.6 | 0.00037 | 0.000334 | 0.000353 |
| Story22 | 66.6 | 0.000405 | 0.000365 | 0.00039 |
| Story21 | 63.6 | 0.000441 | 0.000399 | 0.000422 |
| Story20 | 60.6 | 0.000479 | 0.000433 | 0.000457 |
| Story19 | 57.6 | 0.000517 | 0.000467 | 0.000498 |
| Story18 | 54.6 | 0.000554 | 0.000501 | 0.00054 |
| Story17 | 51.6 | 0.000589 | 0.000535 | 0.000583 |
| Story16 | 48.6 | 0.000622 | 0.000566 | 0.000624 |
| Story15 | 45.6 | 0.000653 | 0.000597 | 0.000664 |
| Story14 | 42.6 | 0.000681 | 0.000625 | 0.0007 |
| Story13 | 39.6 | 0.000707 | 0.000652 | 0.00073 |
| Story12 | 36.6 | 0.000731 | 0.000675 | 0.000754 |
| Story11 | 33.6 | 0.00075 | 0.000696 | 0.000782 |
| Story10 | 30.6 | 0.000766 | 0.000711 | 0.000808 |
| Story9 | 27.6 | 0.000775 | 0.000722 | 0.00083 |
| Story8 | 24.6 | 0.000778 | 0.000724 | 0.000845 |
| Story7 | 21.6 | 0.000771 | 0.000719 | 0.000851 |
| Story6 | 18.6 | 0.000754 | 0.000702 | 0.000846 |
| Story5 | 15.6 | 0.000721 | 0.000672 | 0.000825 |
| Story4 | 12.6 | 0.000669 | 0.000625 | 0.000781 |
| Story3 | 9.6 | 0.000592 | 0.000555 | 0.000704 |
| Story2 | 6.6 | 0.000482 | 0.000454 | 0.00058 |
| Story1 | 3.6 | 0.000308 | 0.000291 | 0.000368 |
| Plinth Level | 0.6 | 0.000083 | 0.000078 | 0.000093 |
| Base | 0 | 0 | 0 | 0 |

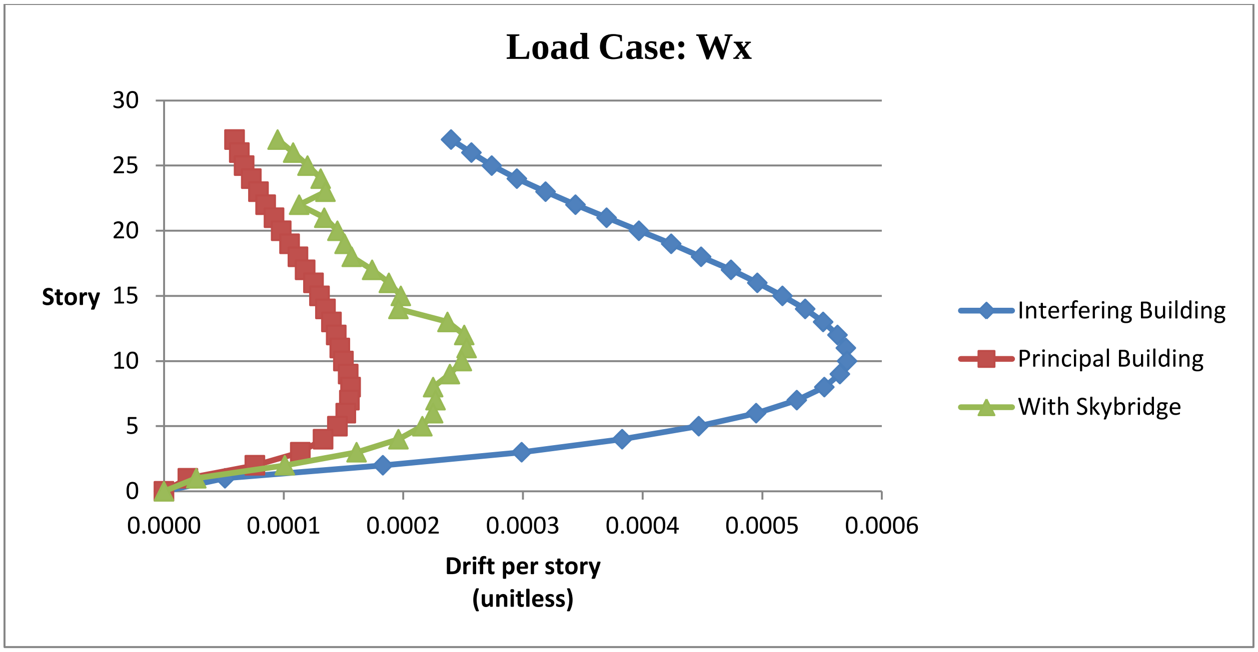



Figure 4.16 Graphical Representation of drift for load case: Wx

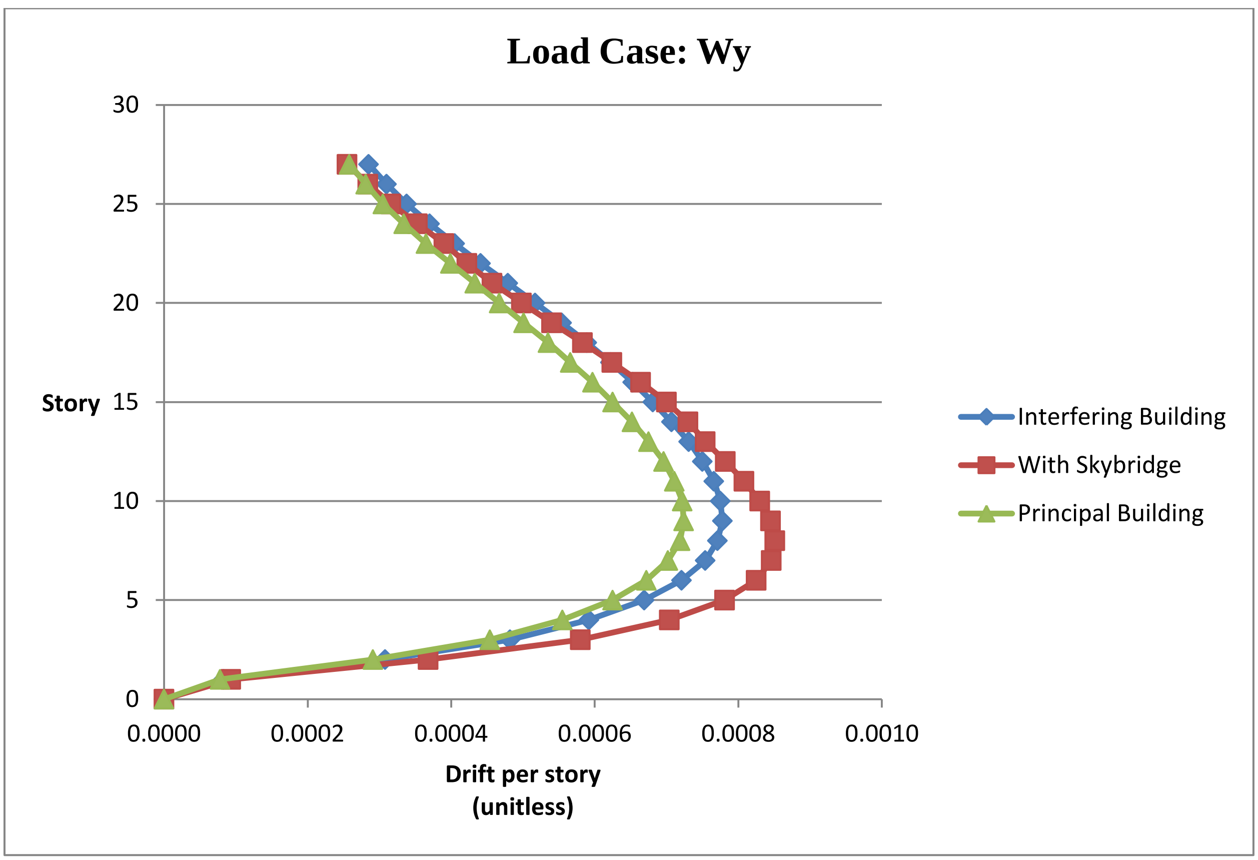



Figure 4.17 Graphical representation of drift for load case: Wy

3. Maximum story Drift for load combination 1.5 (DL-Wx)

Table 4.24 Drift for load combination: 1.5 (DL-Wx)

| Story | Elevation | Interfering Building | Principal Building | With Sky bridge |
|---|---|---|---|---|
| Roof | 78.6 | 0.000359 | 0.000088 | 0.000127 |
| Story25 | 75.6 | 0.000385 | 0.000095 | 0.000146 |
| Story24 | 72.6 | 0.000411 | 0.000101 | 0.000163 |
| Story23 | 69.6 | 0.000443 | 0.000109 | 0.00018 |
| Story22 | 66.6 | 0.000478 | 0.000118 | 0.000185 |
| Story21 | 63.6 | 0.000516 | 0.000128 | 0.000168 |
| Story20 | 60.6 | 0.000555 | 0.000138 | 0.000208 |
| Story19 | 57.6 | 0.000595 | 0.000148 | 0.000218 |
| Story18 | 54.6 | 0.000635 | 0.000158 | 0.000227 |
| Story17 | 51.6 | 0.000674 | 0.000168 | 0.000236 |
| Story16 | 48.6 | 0.00071 | 0.000178 | 0.000262 |
| Story15 | 45.6 | 0.000744 | 0.000187 | 0.000283 |
| Story14 | 42.6 | 0.000775 | 0.000195 | 0.000293 |
| Story13 | 39.6 | 0.000803 | 0.000203 | 0.000292 |
| Story12 | 36.6 | 0.000826 | 0.00021 | 0.000366 |
| Story11 | 33.6 | 0.000844 | 0.000215 | 0.000382 |
| Story10 | 30.6 | 0.000855 | 0.00022 | 0.000385 |
| Story9 | 27.6 | 0.000857 | 0.000225 | 0.000377 |
| Story8 | 24.6 | 0.000848 | 0.000231 | 0.000361 |
| Story7 | 21.6 | 0.000828 | 0.000234 | 0.000339 |
| Story6 | 18.6 | 0.000793 | 0.000233 | 0.00034 |
| Story5 | 15.6 | 0.000742 | 0.000228 | 0.00034 |
| Story4 | 12.6 | 0.00067 | 0.000217 | 0.000327 |
| Story3 | 9.6 | 0.000574 | 0.000199 | 0.000297 |
| Story2 | 6.6 | 0.000448 | 0.000171 | 0.000245 |
| Story1 | 3.6 | 0.000274 | 0.000114 | 0.000154 |
| Plinth Level | 0.6 | 0.000076 | 0.00003 | 0.000041 |
| Base | 0 | 0 | 0 | 0 |

4. Maximum story Drifts for load combination 1.5 (Dead + Wy)

Table 4.25 Drift for load combination: 1.5 (Dead+Wy)

| Story | Elevation | Interfering Building | Principal Building | With Sky bridge |
|---|---|---|---|---|
| Roof | 78.6 | 0.000428 | 0.000387 | 0.000392 |
| Story25 | 75.6 | 0.000466 | 0.000421 | 0.000435 |
| Story24 | 72.6 | 0.000507 | 0.000458 | 0.000484 |
| Story23 | 69.6 | 0.000555 | 0.000501 | 0.000539 |
| Story22 | 66.6 | 0.000607 | 0.000548 | 0.000593 |
| Story21 | 63.6 | 0.000662 | 0.000598 | 0.000639 |
| Story20 | 60.6 | 0.000718 | 0.000649 | 0.000692 |
| Story19 | 57.6 | 0.000775 | 0.000701 | 0.000753 |
| Story18 | 54.6 | 0.000831 | 0.000752 | 0.000816 |
| Story17 | 51.6 | 0.000884 | 0.000802 | 0.00088 |
| Story16 | 48.6 | 0.000933 | 0.00085 | 0.000941 |
| Story15 | 45.6 | 0.000979 | 0.000895 | 0.001001 |
| Story14 | 42.6 | 0.001022 | 0.000938 | 0.001056 |
| Story13 | 39.6 | 0.001061 | 0.000977 | 0.0011 |
| Story12 | 36.6 | 0.001096 | 0.001013 | 0.001137 |
| Story11 | 33.6 | 0.001126 | 0.001043 | 0.001179 |
| Story10 | 30.6 | 0.001149 | 0.001067 | 0.001218 |
| Story9 | 27.6 | 0.001163 | 0.001082 | 0.001249 |
| Story8 | 24.6 | 0.001167 | 0.001086 | 0.001272 |
| Story7 | 21.6 | 0.001157 | 0.001078 | 0.001281 |
| Story6 | 18.6 | 0.00113 | 0.001053 | 0.001273 |
| Story5 | 15.6 | 0.001081 | 0.001007 | 0.00124 |
| Story4 | 12.6 | 0.001004 | 0.000937 | 0.001173 |
| Story3 | 9.6 | 0.000888 | 0.000832 | 0.001057 |
| Story2 | 6.6 | 0.000723 | 0.00068 | 0.00087 |
| Story1 | 3.6 | 0.000463 | 0.000436 | 0.000552 |
| Plinth Level | 0.6 | 0.000124 | 0.000117 | 0.00014 |
| Base | 0 | 0 | 0 | 0 |

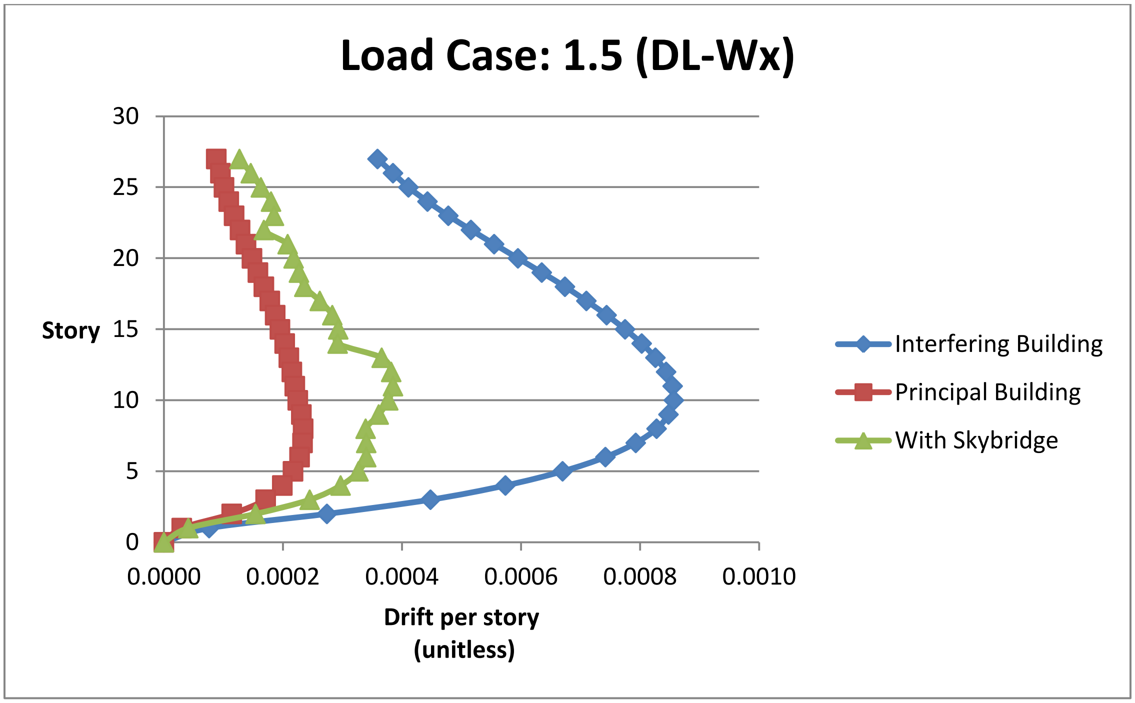



Figure 4.18 Graphical representation of drift for load combination: 1.5 (DL-Wx)

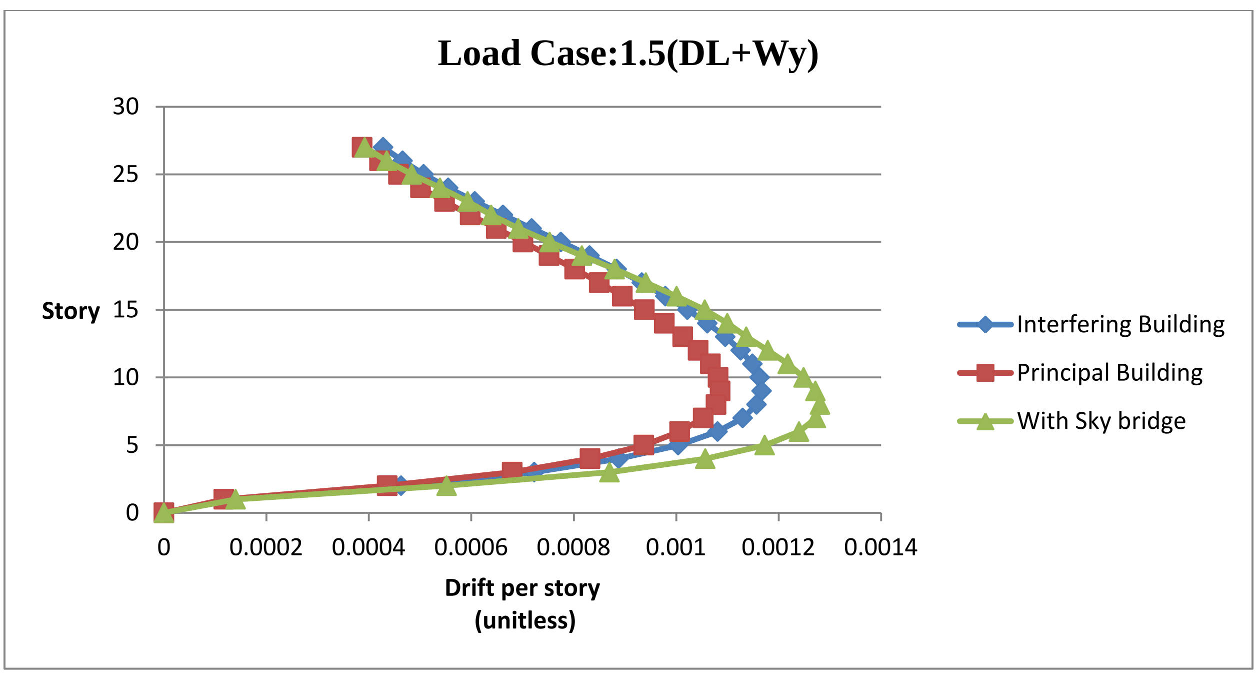



Figure 4.19 Graphical representation of drift for load combination: 1.5 (DL+Wy)

5. Maximum Story Displacements for load case: Wx

Table 4.26 Displacement for load case: Wx

| Story | Elevation | Interfering Building | Principal Building | With Skybridge |
|---|---|---|---|---|
| | m | mm | mm | mm |
| Roof | 78.6 | 33.331 | 9.03 | 12.977 |
| Story25 | 75.6 | 32.612 | 8.854 | 12.691 |
| Story24 | 72.6 | 31.841 | 8.665 | 12.368 |
| Story23 | 69.6 | 31.017 | 8.462 | 12.007 |
| Story22 | 66.6 | 30.131 | 8.244 | 11.613 |
| Story21 | 63.6 | 29.175 | 8.008 | 11.209 |
| Story20 | 60.6 | 28.142 | 7.753 | 10.871 |
| Story19 | 57.6 | 27.031 | 7.478 | 10.534 |
| Story18 | 54.6 | 25.84 | 7.183 | 10.161 |
| Story17 | 51.6 | 24.569 | 6.867 | 9.741 |
| Story16 | 48.6 | 23.221 | 6.532 | 9.269 |
| Story15 | 45.6 | 21.8 | 6.177 | 8.747 |
| Story14 | 42.6 | 20.311 | 5.803 | 8.182 |
| Story13 | 39.6 | 18.759 | 5.413 | 7.588 |
| Story12 | 36.6 | 17.152 | 5.006 | 7.001 |
| Story11 | 33.6 | 15.499 | 4.587 | 6.457 |
| Story10 | 30.6 | 13.811 | 4.156 | 5.901 |
| Story9 | 27.6 | 12.101 | 3.716 | 5.318 |
| Story8 | 24.6 | 10.387 | 3.265 | 4.703 |
| Story7 | 21.6 | 8.691 | 2.804 | 4.06 |
| Story6 | 18.6 | 7.035 | 2.336 | 3.392 |
| Story5 | 15.6 | 5.448 | 1.87 | 2.712 |
| Story4 | 12.6 | 3.963 | 1.414 | 2.036 |
| Story3 | 9.6 | 2.622 | 0.979 | 1.388 |
| Story2 | 6.6 | 1.474 | 0.581 | 0.801 |
| Story1 | 3.6 | 0.578 | 0.24 | 0.318 |
| Plinth Level | 0.6 | 0.031 | 0.012 | 0.016 |
| Base | 0 | 0 | 0 | 0 |

6. Maximum Story Displacements for load case: Wy

Table 4.27 Displacement for load case: Wy

| Story | Elevation | Interfering Building | Principal Building | With Skybridge |
|---|---|---|---|---|
| | m | mm | mm | mm |
| Roof | 78.6 | 45.19 | 41.591 | 47.426 |
| Story25 | 75.6 | 44.334 | 40.816 | 46.66 |
| Story24 | 72.6 | 43.403 | 39.974 | 45.81 |
| Story23 | 69.6 | 42.39 | 39.057 | 44.861 |
| Story22 | 66.6 | 41.28 | 38.055 | 43.802 |
| Story21 | 63.6 | 40.067 | 36.959 | 42.631 |
| Story20 | 60.6 | 38.743 | 35.763 | 41.365 |
| Story19 | 57.6 | 37.307 | 34.465 | 39.993 |
| Story18 | 54.6 | 35.757 | 33.064 | 38.499 |
| Story17 | 51.6 | 34.096 | 31.559 | 36.878 |
| Story16 | 48.6 | 32.328 | 29.955 | 35.13 |
| Story15 | 45.6 | 30.463 | 28.256 | 33.258 |
| Story14 | 42.6 | 28.506 | 26.466 | 31.267 |
| Story13 | 39.6 | 26.462 | 24.59 | 29.166 |
| Story12 | 36.6 | 24.34 | 22.635 | 26.977 |
| Story11 | 33.6 | 22.147 | 20.609 | 24.713 |
| Story10 | 30.6 | 19.896 | 18.522 | 22.366 |
| Story9 | 27.6 | 17.599 | 16.388 | 19.941 |
| Story8 | 24.6 | 15.273 | 14.223 | 17.452 |
| Story7 | 21.6 | 12.94 | 12.072 | 14.918 |
| Story6 | 18.6 | 10.626 | 9.932 | 12.364 |
| Story5 | 15.6 | 8.365 | 7.834 | 9.826 |
| Story4 | 12.6 | 6.203 | 5.82 | 7.351 |
| Story3 | 9.6 | 4.196 | 3.946 | 5.009 |
| Story2 | 6.6 | 2.42 | 2.281 | 2.898 |
| Story1 | 3.6 | 0.974 | 0.92 | 1.159 |
| Plinth Level | 0.6 | 0.05 | 0.047 | 0.056 |
| Base | 0 | 0 | 0 | 0 |

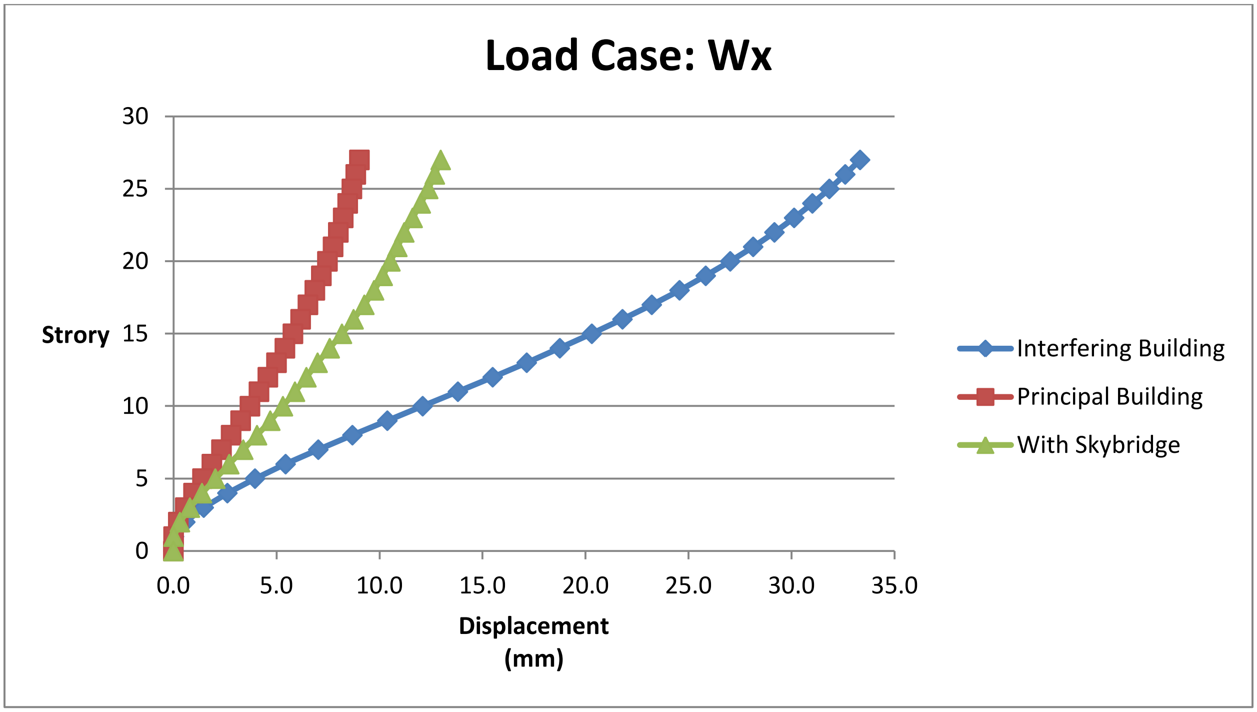



Figure 4.20 Graphical representation of displacement for load case: Wx

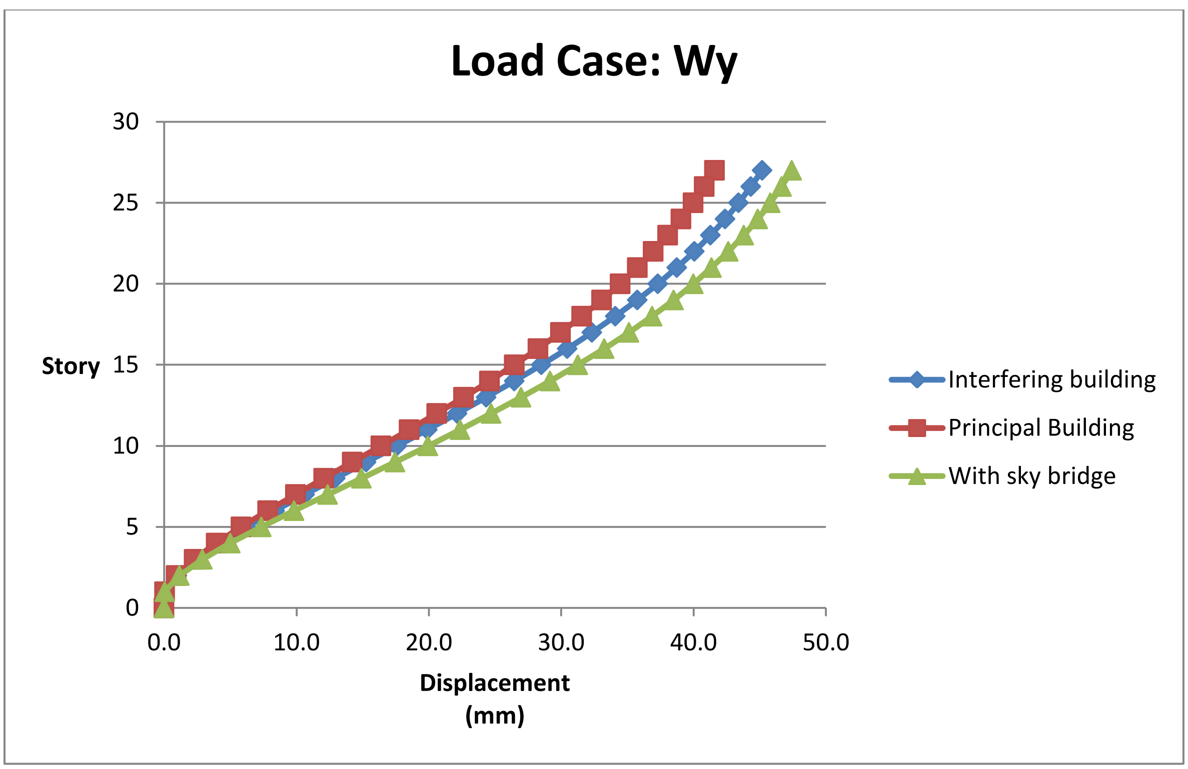



Figure 4.21 Graphical representation of displacement for load case: Wy

7. Maximum Story Displacements for load combination 1.5(DL-Wx)

Table 4.28 Displacement for load combination: 1.5(DL-Wx)

| Story | Elevation | Interfering Building | Principal Building | With Skybridge |
|---|---|---|---|---|
| | m | mm | mm | mm |
| Roof | 78.6 | 49.968 | 13.549 | 19.02 |
| Story25 | 75.6 | 48.891 | 13.285 | 18.646 |
| Story24 | 72.6 | 47.736 | 13.001 | 18.24 |
| Story23 | 69.6 | 46.503 | 12.697 | 17.776 |
| Story22 | 66.6 | 45.175 | 12.369 | 17.254 |
| Story21 | 63.6 | 43.741 | 12.015 | 16.71 |
| Story20 | 60.6 | 42.195 | 11.632 | 16.21 |
| Story19 | 57.6 | 40.53 | 11.22 | 15.731 |
| Story18 | 54.6 | 38.744 | 10.777 | 15.18 |
| Story17 | 51.6 | 36.839 | 10.304 | 14.552 |
| Story16 | 48.6 | 34.818 | 9.8 | 13.843 |
| Story15 | 45.6 | 32.688 | 9.268 | 13.059 |
| Story14 | 42.6 | 30.455 | 8.707 | 12.209 |
| Story13 | 39.6 | 28.129 | 8.121 | 11.33 |
| Story12 | 36.6 | 25.72 | 7.511 | 10.456 |
| Story11 | 33.6 | 23.241 | 6.882 | 9.674 |
| Story10 | 30.6 | 20.71 | 6.236 | 8.859 |
| Story9 | 27.6 | 18.146 | 5.575 | 8 |
| Story8 | 24.6 | 15.576 | 4.899 | 7.091 |
| Story7 | 21.6 | 13.033 | 4.207 | 6.133 |
| Story6 | 18.6 | 10.55 | 3.505 | 5.135 |
| Story5 | 15.6 | 8.17 | 2.806 | 4.114 |
| Story4 | 12.6 | 5.944 | 2.121 | 3.095 |
| Story3 | 9.6 | 3.933 | 1.47 | 2.115 |
| Story2 | 6.6 | 2.211 | 0.871 | 1.223 |
| Story1 | 3.6 | 0.868 | 0.359 | 0.488 |
| Plinth Level | 0.6 | 0.046 | 0.018 | 0.024 |
| Base | 0 | 0 | 0 | 0 |

8. Maximum Story Displacements for load Combination: 1.5(DL+Wy)

Table 4.29: Displacement for load combination: 1.5(DL+Wy)

| Story | Elevation | Interfering Building | Principal Building | With SkyBridge |
|---|---|---|---|---|
| | m | mm | mm | mm |
| Roof | 78.6 | 67.798 | 62.399 | 71.549 |
| Story25 | 75.6 | 66.513 | 61.236 | 70.374 |
| Story24 | 72.6 | 65.116 | 59.973 | 69.07 |
| Story23 | 69.6 | 63.596 | 58.598 | 67.619 |
| Story22 | 66.6 | 61.932 | 57.094 | 66.003 |
| Story21 | 63.6 | 60.111 | 55.449 | 64.222 |
| Story20 | 60.6 | 58.126 | 53.655 | 62.307 |
| Story19 | 57.6 | 55.971 | 51.708 | 60.232 |
| Story18 | 54.6 | 53.646 | 49.606 | 57.973 |
| Story17 | 51.6 | 51.153 | 47.349 | 55.524 |
| Story16 | 48.6 | 48.502 | 44.942 | 52.885 |
| Story15 | 45.6 | 45.704 | 42.393 | 50.06 |
| Story14 | 42.6 | 42.767 | 39.707 | 47.058 |
| Story13 | 39.6 | 39.701 | 36.893 | 43.89 |
| Story12 | 36.6 | 36.517 | 33.961 | 40.59 |
| Story11 | 33.6 | 33.229 | 30.921 | 37.178 |
| Story10 | 30.6 | 29.851 | 27.791 | 33.64 |
| Story9 | 27.6 | 26.405 | 24.589 | 29.985 |
| Story8 | 24.6 | 22.916 | 21.342 | 26.236 |
| Story7 | 21.6 | 19.416 | 18.111 | 22.422 |
| Story6 | 18.6 | 15.944 | 14.901 | 18.579 |
| Story5 | 15.6 | 12.553 | 11.754 | 14.761 |
| Story4 | 12.6 | 9.309 | 8.734 | 11.04 |
| Story3 | 9.6 | 6.297 | 5.922 | 7.52 |
| Story2 | 6.6 | 3.634 | 3.424 | 4.35 |
| Story1 | 3.6 | 1.464 | 1.383 | 1.74 |
| Plinth Level | 0.6 | 0.075 | 0.071 | 0.084 |
| Base | 0 | 0 | 0 | 0 |

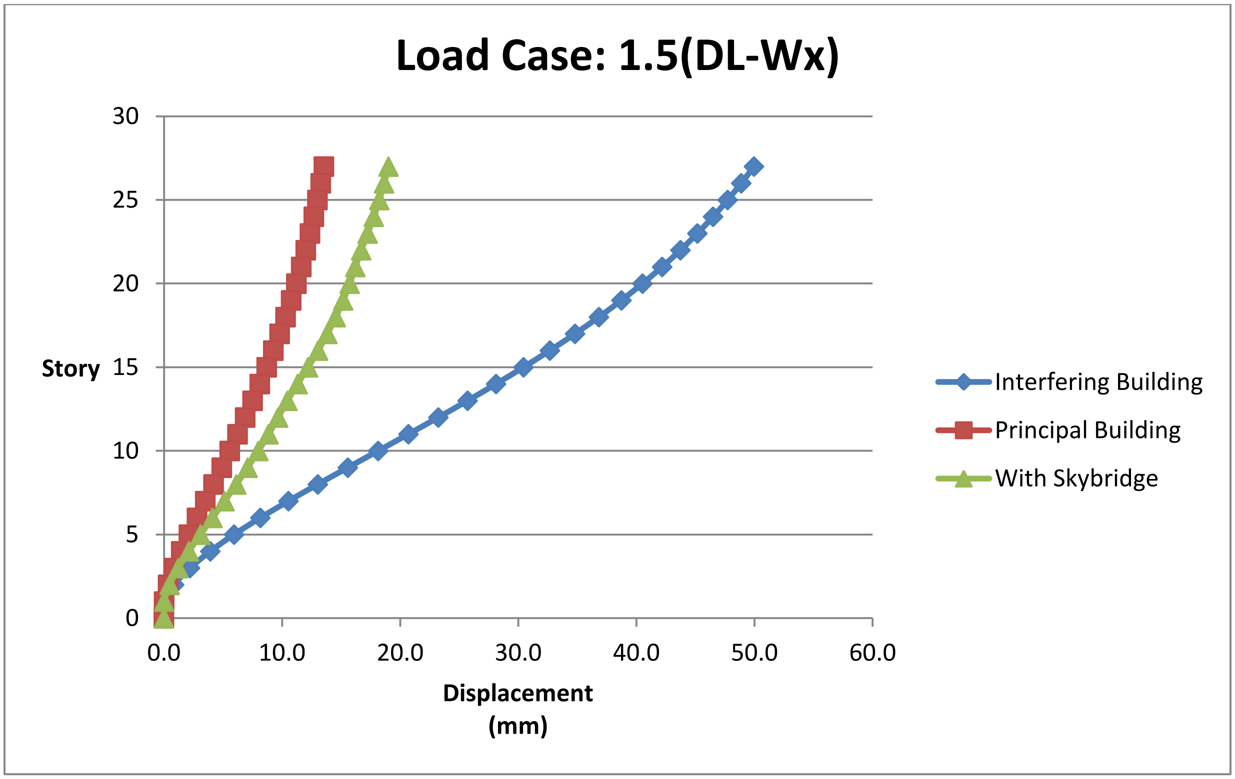



Figure 4.22 Graphical representation of displacement for load combination: 1.5(DL-Wx)

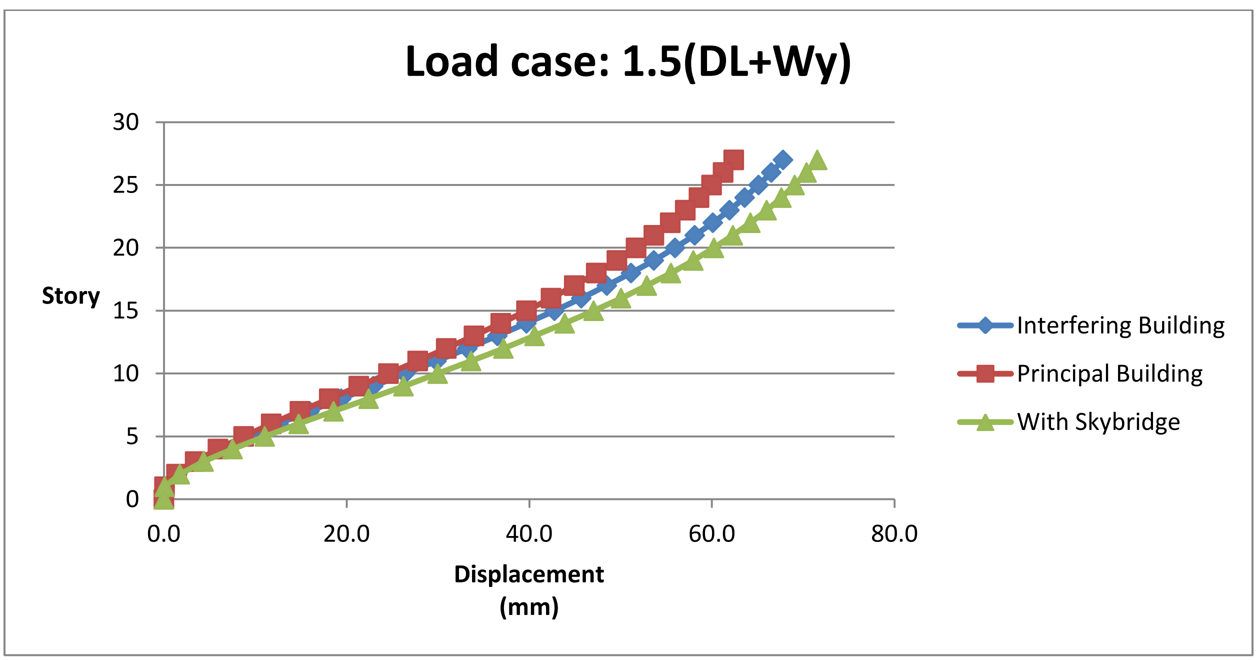



Figure 4.23 Graphical representation of displacement for load combination: 1.5(DL+Wy)

9. Base reactions

Table 4.30 Base Reactions as calculated by ETABS

| Load Case | | Fx (kN) | Fy (kN) | Fz (kN) | Mx (kNm) | My(kNm) | Mz(kNm) |
|---|---|---|---|---|---|---|---|
| Wx | IB | -3387 | 97 | 0 | -3027 | -158227 | 40174 |
| | PB | 847 | 71 | 0 | -3164 | 38825 | -5745 |
| | N | -2305 | 3.44 | 0 | -1766 | -107030 | 29311 |
| Wy | IB | 7 | -4185 | 0 | 196825 | 280.5 | -56606 |
| | PB | 234 | -3933 | 0 | 181618 | 4566 | -56027 |
| | N | -73 | -8113 | 0 | 368770 | -4349 | -273652 |
| 1.2(DL+LL+Wx) | IB | -4065 | 117 | 432758 | 4973083 | -6031481 | 48208.5 |
| | PB | 1016 | 85 | 432859 | 4974084 | -5797007 | -6894 |
| | N | -2766 | 4 | 878994 | 10106313 | -30456438 | 35174 |
| 1.2(DL+LL+Wy) | IB | 8 | -5022.5 | 432758 | 5212905 | -5841272 | -67927 |
| | PB | 281 | -4720 | 432859 | 5195822 | -5838117 | -67233 |
| | N | -88 | -9736 | 878994 | 10550956 | -30333220 | -328381 |
| 1.5(DL-Wx) | IB | 5081 | -146 | 468682 | 5394380 | -6089086 | -60260.5 |
| | PB | -1270 | -106 | 468808 | 5396043 | -6387149 | 8617 |
| | N | 3457 | -5 | 953563 | 10968630 | -32740781 | -43965 |
| 1.5(DL+Wy) | IB | 10 | -6278 | 468682 | 5685077 | -6326006 | -84908.5 |
| | PB | 351 | -5900 | 468808 | 5663724 | -6322062 | -84041 |
| | N | -110 | -12170 | 953563 | 11519136 | -32907849 | -410477 |

Note: N indicates ‘with sky bridge’ results

# Chapter-5

# Conclusions and Future Scope

## 5.1 Conclusions

In this work the analysis is carried out to study the lateral drift of the structurally coupled buildings connected by two sky bridges at 12$^{th}$ floor and 20$^{th}$ floor using earthquake static and dynamic analysis and wind static analysis. The buildings are 25 stories high. The comparisons are drawn between the responses, namely, drift and displacement of non-connected and connected structures. The following conclusions are drawn:

1. From Tables 4.11 and 4.12 it can be observed that for load case Ex around 5% reduction in drift can be obtained while for load case Ey only 3% can be achieved. Similarly, from Table 4.13, for Response Spectrum load case 6.44% reduction can be obtained in X direction but only 3.65% in Y direction. This is because sky bridge is connected in X direction so it provides lateral stability in that particular direction.
2. Maximum reduction in drift can be obtained particularly in X direction if dynamic analysis is done. Also the critical load combination that can be obtained for static analysis is 1.5(DL+Ex) in X direction and 1.5(DL-Ey) in Y direction. From Tables 4.14 and 4.15, these have 5% and 3.76% reduction in drift values respectively.
3. Thus from tables 4.16 and 4.17, overall displacement saw a reduction of 4.7% and 3.37% for Ex and Ey load cases. The maximum reduction in displacement is obtained for dynamic analysis-6.1% and 3.5% in X and Y direction respectively as can be calculated from table 4.18.
4. From Tables 4.22, 4.23, 4.26 and 4.27 it can be observed that the drift and displacement due to wind loads of second building has reduced in both directions. This can be attributed to the shielding effects that the first building have on the other building.
5. From Table 4.22, the reduction obtained in the maximum response (drift) of the two buildings by connecting sky bridges is around 55% in X direction. But response has increased up to 10 % due to increased wind loads on outer edges of the faces of the buildings connected to sky bridge as seen from Table 4.23.
6. The critical load combinations are 1.5(DL-Wx) and 1.5(DL+Wy) in X and Y direction respectively. These saw a reduction of 55% and increase of 9.7% in drift values and

reduction of 61.9% and increase in 5.5% in displacement values respectively as observed from tables 4.24, 4.25, 4.28 and 4.29.

7. The reduction in drift and displacement is much greater in wind analysis than earthquake analysis because of the nature of the structural frame. The RC frame is quite heavy thus rendering the lateral stability provided by the sky bridge pretty much useless.
8. Thus it can be concluded that in case wind loads govern the design and the buildings are structurally coupled, the members should be designed for the critical load combinations independently in both X and Y directions for economic purpose owing to a large reduction in drift in one direction and slight increase in other direction.

## 5.2 Future scope of the work

The following studies can be done for more accurate and better understanding of the present study:

1. Further studies can be carried out using a different type of structure like steel framed structure or shear wall-plate slab structure, etc.
2. Wind Dynamic analysis can be carried for proper understanding of sky bridge and across wind behavior of the structure.
3. More studies can be done by increasing the overall height of building so that wind loads govern the design. Also for the same purpose shape of the structure can be changed.
4. Moreover, studies can be done by changing earthquake and wind parameters like zone, soil type, terrain category, etc.

# References


1. Abada, G. (2004). "2004 On Site Review Report: Petronas Office Towers, Kuala Lumpur, Malaysia."
2. CSI Knowledge base (2010). “Etabs.”< https://wiki.csiamerica.com/display/etabs/Home> (July 3, 2017).
3. CSI Knowledge base (2010). “P-Delta Analysis Parameters.” < https://wiki.csiamerica.com/display/etabs/P-Delta+analysis+parameters> (March 23, 2017).
4. CED 38 (10639)WC(Bureau of Indian Standards).,2016.Criteria for Structural Safety of Tall Buildings.
5. Davidson, B.J., Fenwick, R.C., and Chung, B.T.(1992). “P-delta effects in multi-storey structural design.” The 10th World Conference on Earthquake Engineering, Balkema, Rotterdam.
6. Engineers, (2010). "The Pinnacle@Duxton." *The Singapore Engineer*, Jun 2010
7. Haklar, T. (2009). "10 Fascinating Skybridges." <http://www.theworldgeography.com/2013/08/skybridges.html>. (July 3, 2017)
8. Holl, S.A. (2009) "Linked Hybrid." <http://www.stevenholl.com/projectdetail.php?id=58>.(July 4, 2017).
9. IRC:6 (Indian Roads Congress).,2014. Standard Specifications and Code of Practice for Road Bridges. Section-II Loads and Stresses.
10. IS:1893 (Bureau of Indian Standards).,2002. Indian Standard Criteria for Earthquake Resistant Design of Structures. Part 1 General Provisions and Buildings (Fifth Revision).
11. IS:875 (Bureau of Indian Standards).,1989. Indian Standard Code of Practice for Design Loads for Buildings and Structures. Part 1 Dead loads- Unit Weights of Building Materials and Stored Materials (Second Revision).
12. IS:875 (Bureau of Indian Standards).,1989. Indian Standard Code of Practice for Design Loads for Buildings and Structures. Part 3 Wind Loads (Second Revision)
13. Kareem, A., Kijewski, T., and Tamura, X., (1999). “Mitagation Of Motions Of Tall Buildings With Specific Exampels Of Recent Applications” *Wind and Structures*., 2(3), 201-251.

14. Kheyari, P., Dalui, S.K.(2015). “Estimation of Wind Load on a Tall Building under Interference effects: A Case Study.” Jordan Journal of Civil Engineering., 9(1).
15. Kim, W., Tamura, Y., and Yoshida, A.,(2009). “Interference effects of Two Buildings on Peak Wind Pressures.” The Seventh Asia-Pacific Conference on Wind Engineering, Taipei, Taiwan.
16. Kiran, M .U., Shivananda, S. M., and Mahantesha, O. (2016). “A Study Of Lateral Drift Controlling Between Two Buildings By Connecting Sky Bridge.” International Journal of Civil and Structural Engineering Research., 4(1), 266-273.
17. Lu, X. (2009). "Shaking table model tests on a complex high-rise building with two towers of different height connected by trusses." Structural Design of Tall and Special Buildings, 18(7), 765-788.
18. Luong, A., and Kwok, M. (2012). "Finding Structural Solutions by Connecting Towers." *CTBUH Journal*(III), 26-31.
19. McCall, A. J.T.(2013). "Structural Analysis and Optimization of Skyscrapers Connected with Skybridges and Atria" . *All Theses and Dissertations.* Paper 3829.
20. Ming, L. J., Suan, T. P., and Toh, W. (2010). "HDB's next generation of eco-districts at Punggol and eco-modernisation of existing towns." *The IES Journal Part A: Civil & Structural Engineering*, 3(3), 203-209.
21. NewScientist (2006). "No way out?" New Scientist, 189(2538), 40-43.
22. Nishimura, A. (2011). "Base-isolated super high-rise RC building composed of three connected towers with vibration control systems." Structural Concrete, 12(2), 94-108.
23. Seima. (2012). “Shanghai World Financial Center at Night.” <http://www.panoramio.com/photo/72316323> (June 5, 2017).
24. Timoshenko, S.P. and Gore, J.M.(1977). “Mechanics of Materials.” Van Nostrand, Reinhold.
25. Verma, S.K.(2014). “Wind loads on structurally coupled through single bridge tall buildings.” International Journal of Civil and Structural Engineering., 4(3), 469-476.
26. Wada, A.(1992). “Drift design of tall buildings” The 10th World Conference on Earthquake Engineering, Balkema, Rotterdam.
27. WikiArquitectura (2010). "Umeda Sky Building." *Buildings of the World*, <http://en.wikiarquitectura.com/index.php/Umeda_sky_building>. (May 5, 2017).

28. Wikipedia (2010). “Island Tower Sky Club.” <https://en.wikipedia.org/wiki/Island_Tower_Sky_Club> (April 17, 2017).
29. Wikipedia(2017). “Skyway.” < https://en.wikipedia.org/wiki/Skyway>(Feb. 19, 2017)
30. Wood, A., Wan-Ki, C., and McGrail, D.(2005). “The Skybridge as an Evacuation Option for Tall Buildings in High-Rise Cities in the Far East.” Journal of Applied Fire Science, 13(II), 113-124.