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Seismic Analysis of Tall Buildings Connected with Sky Bridge

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Abstract: Sky bridges have gained popularity in recent years due to their aesthetic appeal and the recreational facilities they provide. They also serve several structural purposes, such as controlling displacement and drift. Typically, steel trusses or composite materials are used to construct sky bridges. However, this paper proposes an innovative approach using reinforced concrete (RCC) material for constructing sky bridges. The use of RCC for constructing sky bridges has several advantages, including increased durability and reduced maintenance requirements. Although the sky bridges are rigidly connected with End moments released on both sides which provide improved damping in buildings. The study utilizes ETABS19 software to model and analyse the building. This paper focused primarily on the earthquake forces that act on buildings. In this research, two buildings of similar heights i.e., 20, 24 and 28 stories are connected with one, two, or three sky bridges at different floor levels. The objective is to determine the most effective location and number of sky bridges to achieve optimal solutions. The study aims to compare the structural parameters of RCC sky bridges such as storey displacement, storey drift and base shear. This research provides valuable insights into the use of RCC material for constructing sky bridges and can serve as a basis for future studies on the topic.

Keywords: Sky bridge, Seismic analysis, Tall buildings, Earthquake force, Storey displacement, Storey drift, RCC material sky bridge, Response spectrum.

I. INTRODUCTION

As the world's population continues to increase and move from rural areas to urban centers, the need for additional working and living space is also increasing. Urban areas have few options to adequately meet this rising demand because of the high cost of land and the increased number of people living in a relatively small area. A typical strategy to address this growing demand to satisfy this increased need for physical space will be the creation of vertical real estate in the form of skyscrapers.

One of the major problems with tall building design is horizontal displacement, which is related to the dynamic characteristics of the building during earthquakes and high winds. The amount of side sway between two adjacent floors of a building caused by lateral wind and seismic load is known as lateral or storey drift. When a wall experiences wind or earthquake loads, its horizontal displacement between supports is referred to as deflection. The amount of sag caused by gravity or other vertical loading is known as the vertical deflection of a floor or roof structural element.

The concept of using a sky bridge to connect two or more buildings has been existing for a while. A tall building with a sky bridge is a unique architectural structure that has become increasingly popular in recent years.

However, constructing a tall building with a sky bridge comes with its own challenges. The design and construction of such a structure must take into consideration various factors, such as wind load, seismic load and safety regulations.

Figure 1 Marina Bay sands Singapore

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Despite the challenges, tall buildings with sky bridges have become an iconic feature of many modern cities around the world, offering a unique blend of functionality, aesthetics, and innovation.

In addition, sky bridges can offer several practical advantages to building owners and occupants. They provide a safe and secure means of accessing different parts of the building, reducing the need for multiple elevators and staircases. Sky bridges also improve the building's energy efficiency by allowing natural light and ventilation to enter the structure.

Baviskar et al. (2020) [5] It has been found that fluid viscous dampers reduce earthquake responses very effectively when the capacity of the dampers is increased. B. Kiriparan et al. (2020) [6] When the bridge is relatively less stiff, roller connected sky bridges are used. Jamal Ahmad Alomari, (2021) [16] When two buildings are connected by sky bridges, their individual modal shapes may change significantly. These changes may include torsional effects in the initially translational mode shapes of the individual buildings.

II. SKY BRIDGE

A multi-storey building connected by a sky bridge is a structure consisting of two or more buildings that are connected by a pedestrian bridge at an elevated height. The sky bridge is usually enclosed and may have a glass or steel structure. Sky bridges are typically made of steel, concrete, or other durable materials, and are designed to withstand the weight of pedestrian traffic, as well as the elements. They may be supported by cables, pillars, or other structural elements, and may be designed to accommodate pedestrian traffic. The bridge provides a safe and efficient way for people to move between the two buildings, often without having to navigate street-level traffic.

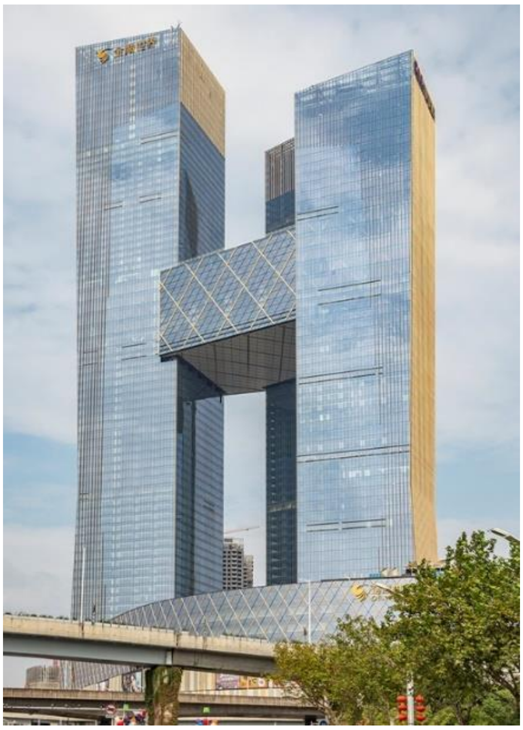

Figure 2 Golden Eagle tower

From a structural point of view, the sky bridge provides noticeable lateral resistance to the building towers. This is because the sky bridge behaves like a floor slab with a horizontal diaphragm. Note that floor systems constructed of slabs behave like horizontal diaphragms with extremely high horizontal stiffness. They help to distribute the lateral load into vertical structural elements such as walls and columns apart from resisting vertical load.

Some notable examples of multi-storey buildings connected by sky bridges include the Petronas Towers in Kuala Lumpur, Malaysia, The gate of the orient in China, Island tower sky club in Japan, and the Marina Bay Sands in Singapore.

Purposes Of Sky Bridges

Sky bridges serve a variety of purposes, like

- Sky bridges can help to reduce the sway caused by wind or earthquakes.
- Sky bridges can connect multiple buildings, making it easier for people to move from one building to another without having to go outside.
- This is especially useful in areas with extreme weather conditions, where it may be difficult or unsafe to go outside.
- Increased safety: Sky bridges can provide an emergency escape route during fire and terrorist attacks.

Structural consideration

Buildings connected by sky bridges have different structural behaviour depending on where they are located, how stiff they are, and how they are connected to the other buildings. Various types of connections are used to connect the sky bridge to the building, such as rollers, hinges, and rigid connections.

Roller or slider connections are often used in high-rise buildings to allow for independent movement and sway of the structure under lateral loading, such as wind or earthquakes. These connections are designed to allow the building to move laterally while maintaining its stability and structural integrity as is shown in figure 3(a)

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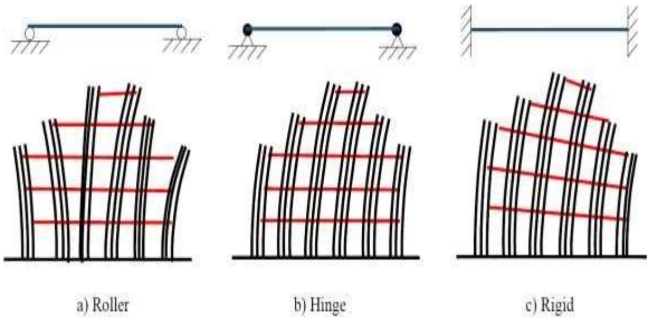

Figure 3 (a) Roller (b) Hinge (c) Rigid connections

When these sky bridges are hinge-connected to the skyscrapers, they can constrain the skyscrapers to sway in unison. This means that when one skyscraper sways due to an earthquake or other external forces, the other connected skyscrapers will also sway in the same direction and at the same time as is shown in Figure 3(b).

Sky bridges that are rigidly connected to skyscrapers can indeed constrain the skyscrapers to deflect as a cantilever unit. This is because the bridge acts as a rigid link between the two buildings, effectively transferring loads between them. When external forces such as earthquakes or seismic activity act on the building, the bridge can help to distribute those forces evenly between the two structures, reducing the stresses on individual components as is shown in Figure 3(c).

The Petronas Twin Towers in Kuala Lumpur, Malaysia, shown in Figure 4 is an example of the roller connection sky bridge. The sky bridge connects the two towers on the 41st and 42nd floors, which are 170 meters (558 feet) above ground. The bridge is 58 meters (190 feet) long and weighs about 750 metric tons.

The Marina Bay Sands complex in Singapore, shown in Figure 1 is an example of the hinge-connected sky bridge. The sky bridge, called the Sands Sky Park, is located on the 57th floor of the complex and is designed as a cantilever truss structure with two hinges. The Sands Sky Park is an engineering marvel that spans 340 meters across the top of the three hotel towers that make up the Marina Bay Sands complex.

Figure 4 Petronas tower

Island tower sky club is a high-rise building located in Fukuoka City; Japan is a three 42-storey apartment building shown in the figure. The building towers have three-fold rotational symmetry. The towers are connected at the 15th, 26th, and 37th stories by truss sky bridges with hinged-joint.

III. NUMERICAL STUDY

For the current work, Modelling of two similar-height buildings of 20, 24, and 28 stories connected by an RCC material sky bridge, with heights of 61.5m, 73.5m, and 85.5m, respectively in ETABS19 Software. Seismic analysis is carried out is located in seismic zone IV. A comparison is made between parameters such as maximum top storey lateral displacement, maximum base shear, maximum storey displacement, and maximum storey drift.

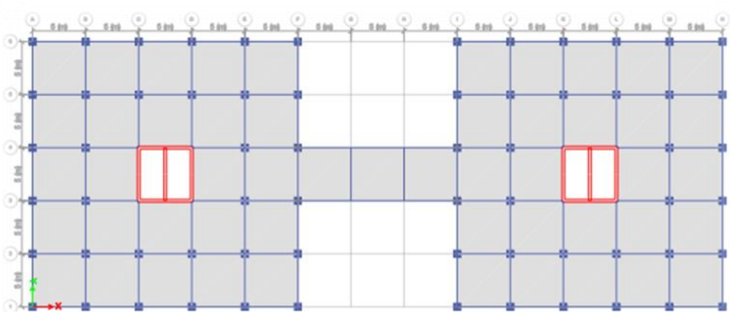

Figure 5 Building Model Plan

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For this study create 33 different ETABS19 models of similar height buildings for parametric comparison. The building details, and Loads specification are given in below Table 1. & Table 2.

Table 1 Building details

Details of Building Model	
Number of storey's	20, 24 & 28
Plan dimensions	25m X 25m
Spacing between buildings	15m
Total height of each tower	61.5m, 73.5m & 85.5m
Storey height	3m
Slab Thickness	120mm
Shear Wall Thickness	250mm
Column Size	750x750mm
Beam size in Towers	300x500mm
Beam size in Sky bridge	300x750mm

Table 2 Load Specifications

Dead Load	As per IS 875 (Part 1)-1987
Live Load	Roof: 1.5 kN/m^2 Other Floors: 2.5 kN/m^2 Sky Bridge: 4 kN/m^2
Floor Finish	0.5 kN/m^2
Wall Load	Roof: 1.5 kN/m^2 Outer:13.8 kN/m^2
Earthquake load	As per IS 1893 (part 1)-2016

Table 3 Seismic factors

Code	IS 1893:2016
Seismic zone	IV
Importance factor	1
Soil conditions	Medium
Time Period (Ta)	Manually calculated 28 floors: 1.539 sec 24 floors: 1.323 sec 20 floors: 1.107 sec

Fe500 has been used as reinforcement in this study along with concrete of grade M30. Considering the density of brick masonry 20 kN/m3. The Seismic factors of the study are given in Table-3.

In this analysis, the response spectrum is calculated with a damping of 5% and the response reduction factor is five, the same factor that is used in IS 1893 (part 1) for special RC moment resisting frames. and use medium soil conditions. for this study time period is manually calculated as per IS code 1893 (part 1) formula.

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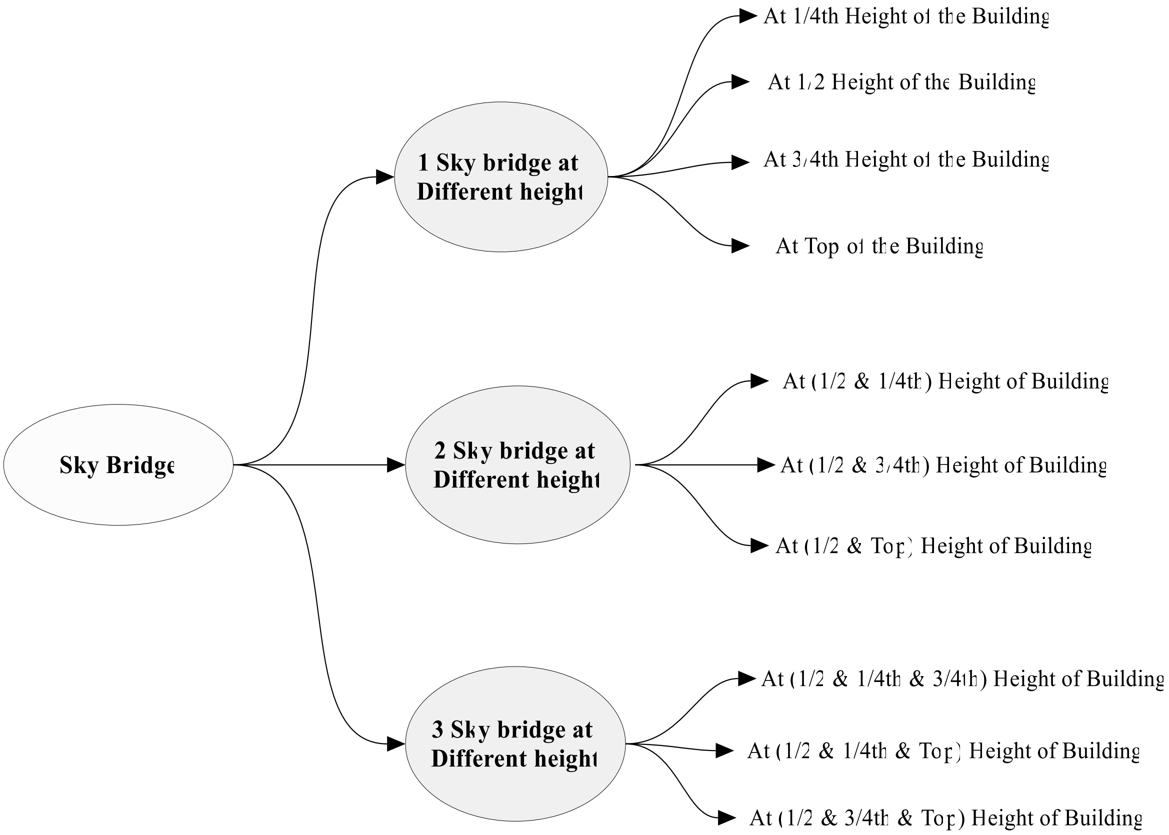
A. Location of sky bridges

For the numerical study, a sky bridge was used to connect 20, 24 and 28 storey similar-height buildings at various locations for 10 different configurations, with one sky bridge at a time on 1/4th, 1/2, 3/4th and top height of the building, with two sky bridges at a time (1/2 & 1/4th), (1/2 & 3/4th) and (1/2 & Top) height of the building, with three sky bridges at a time (1/2 & 1/4th & Top), (1/2 & 1/4th & Top) and (1/2 & 3/4th & Top) height of the building.

A graphic representation is given in Figure.



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B. Models

- 20 Storey models

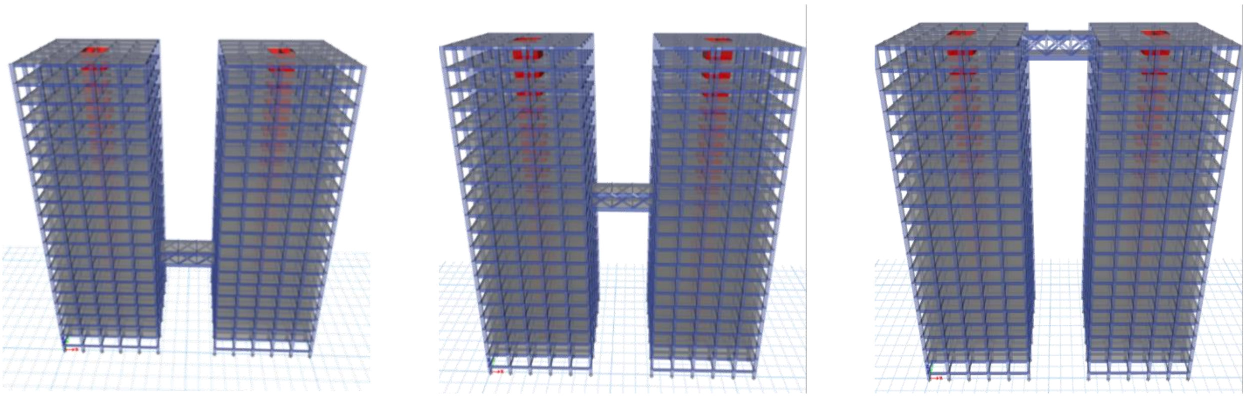

Figure 6 One sky bridge at a time on the 5th floor, 10th floor, 20th floor

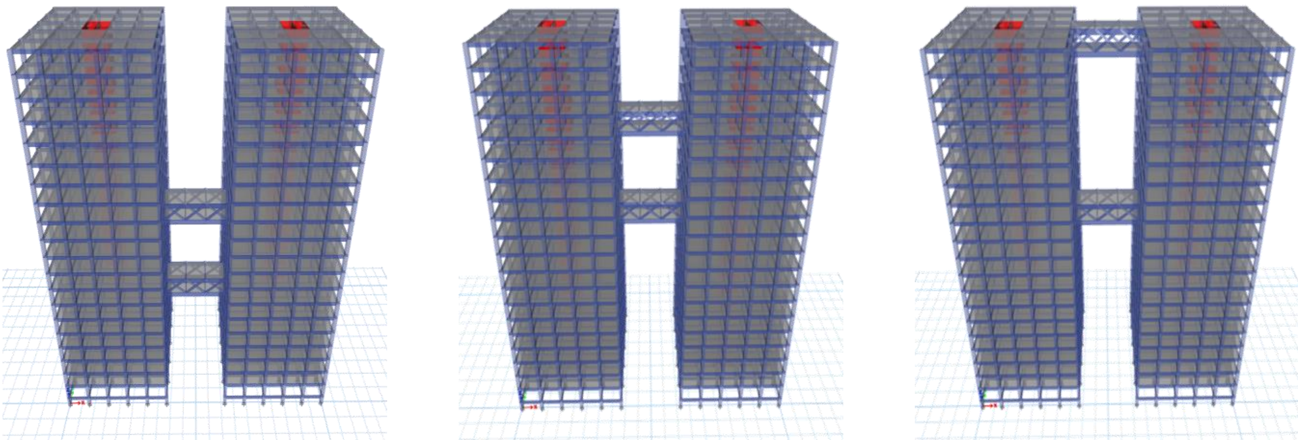

Figure 7 Two skybridge at a time on the 10th & 5th floor, 10th & 15th floor, 10th & 20th floor

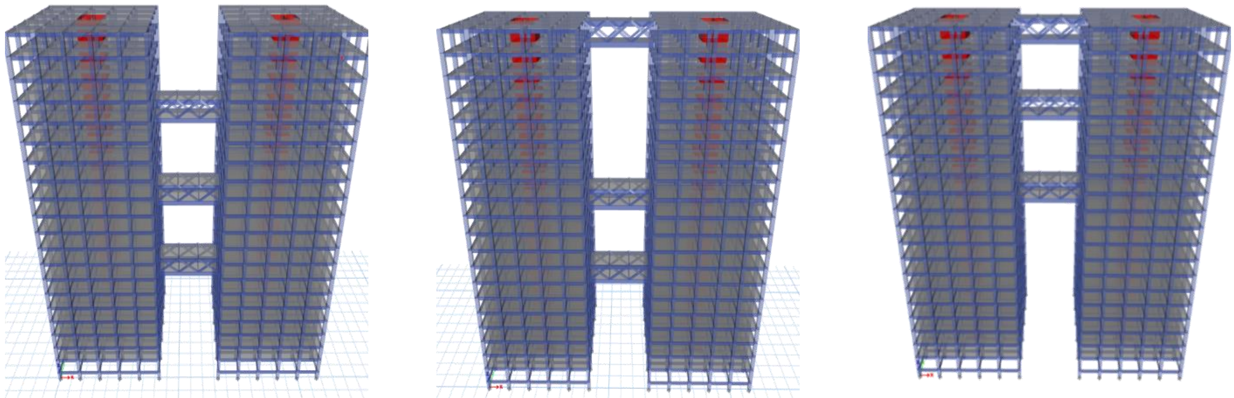

Figure 8 Three skybridge at a time on the 10th & 5th & 15th floor, 10th & 5th & 20th floor, 10th & 15th & 20th floor

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- 24 Storey models

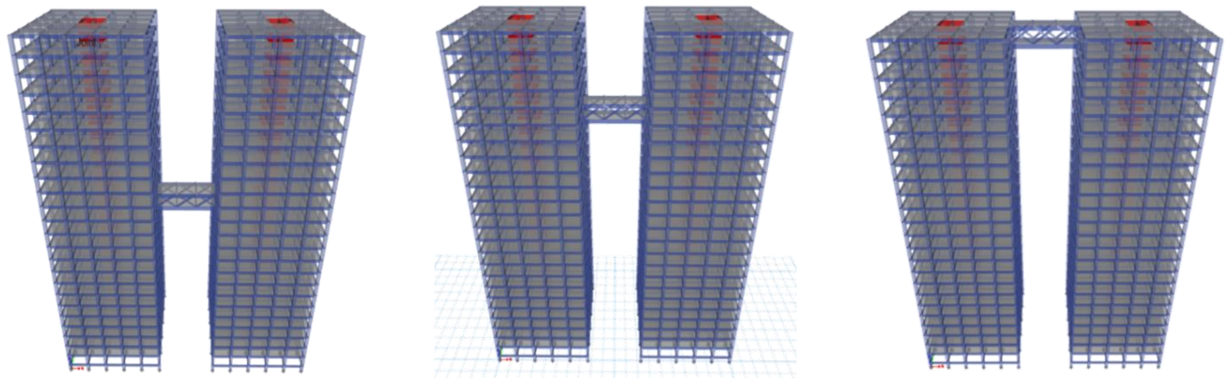


Figure 9 One sky bridge at a time on the 10th floor, 18th floor, 24th floor

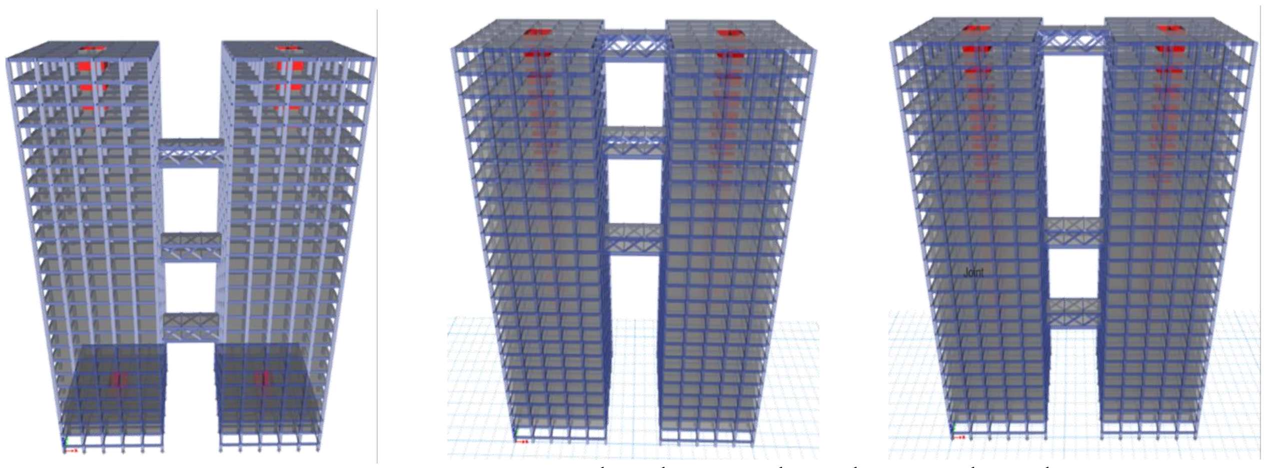
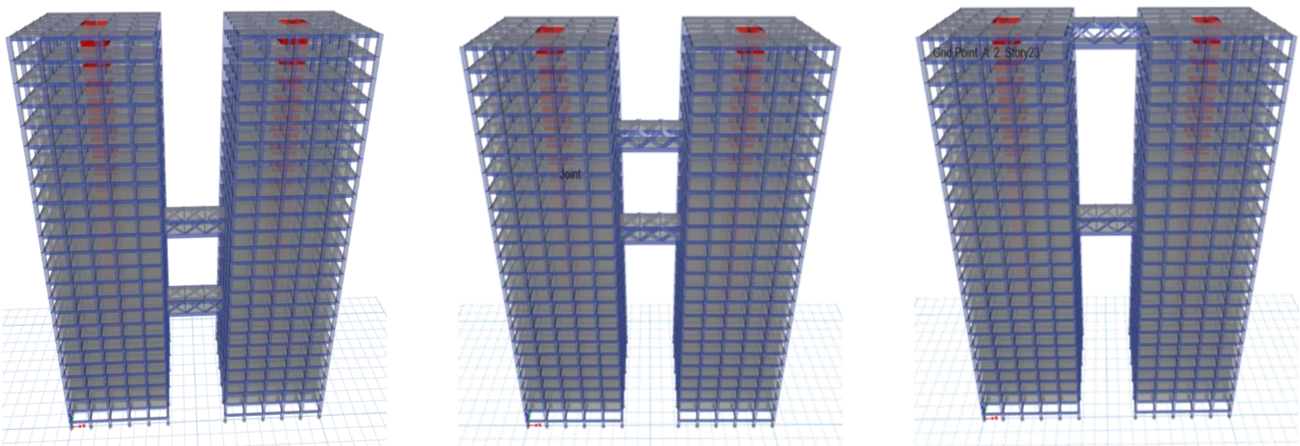


Figure 10 Two skybridge at a time on the 12th & 6th floor, 12th & 18th floor, 12th & 24th floor



\Figure 11 Three skybridge at a time on the 12th & 6th & 18th floor, 12th & 6th & 24th floor, 12th & 18th & 24th floor

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- 28 Storey models

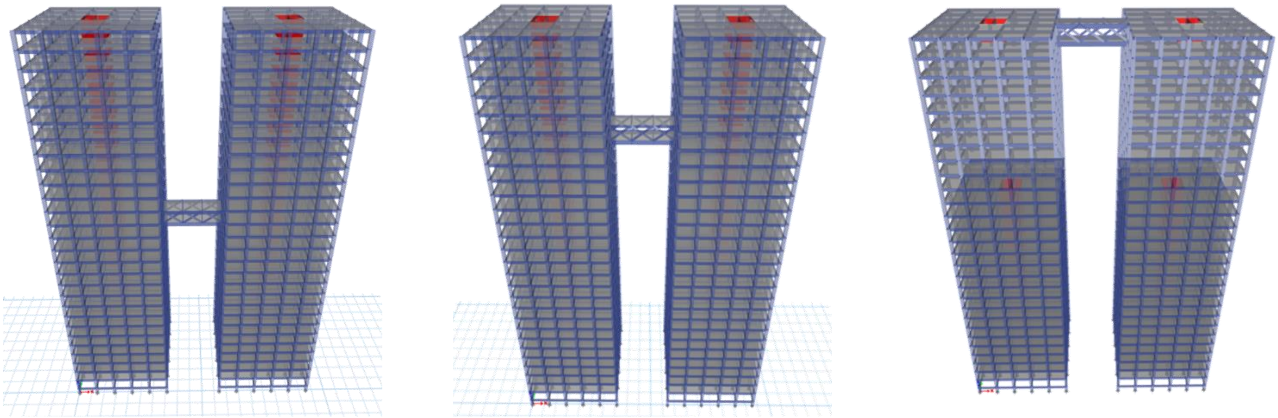

Figure 12 One sky bridge at a time on the 14th floor, 21st floor, 28th floor

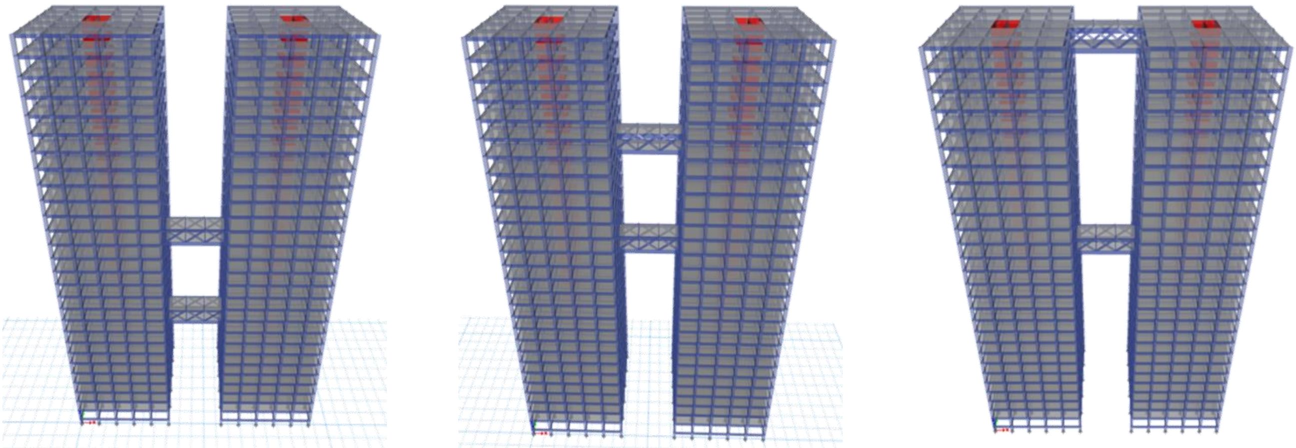

Figure 13 Two skybridge at a time on the 14th & 7th floor, 14th & 21th floor, 14th & 28th floor

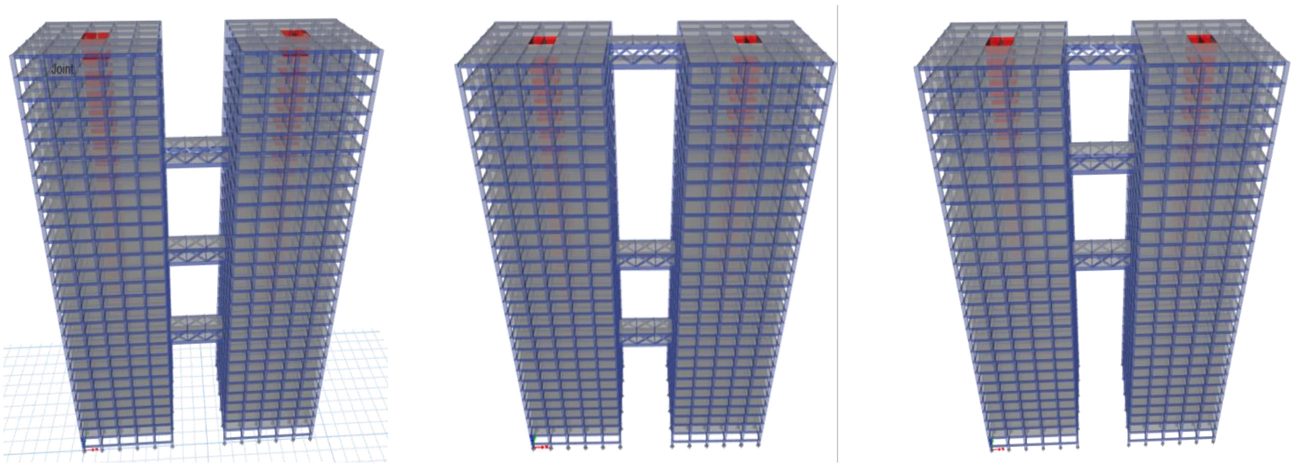

Figure 14 Three skybridge at a time on the 14th & 7th & 21th floor, 14th & 7th & 28th floor, 14th & 21th & 28th floor

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IV. RESULTS AND DISCUSSION

A. 20 storey building results

1) 20 storey building maximum storey displacement

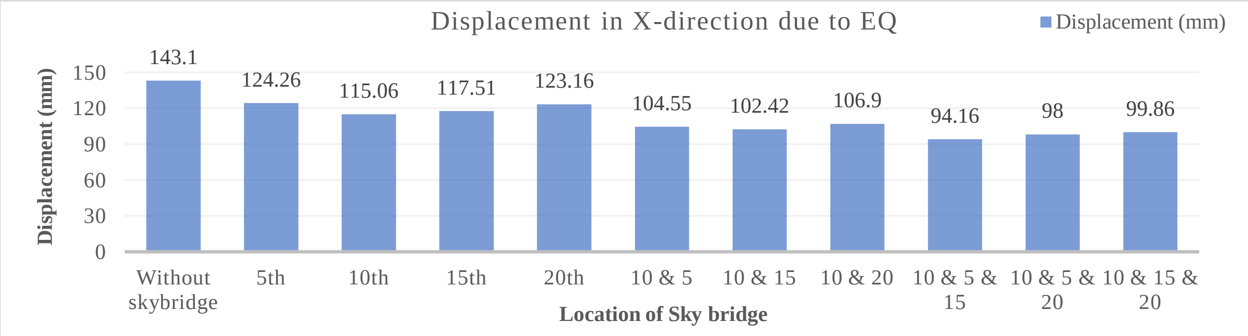

Figure 15 20 storey building Displacement in X-direction due to EQ

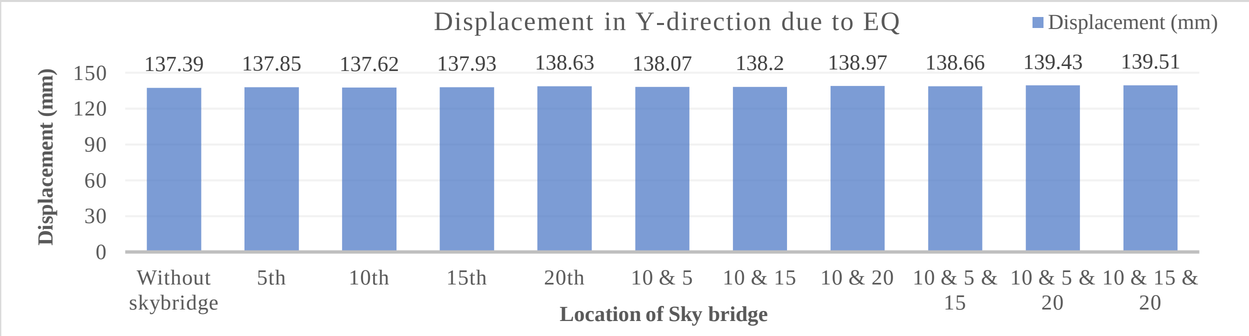

Figure 16 20 storey building Displacement in Y-direction due to EQ

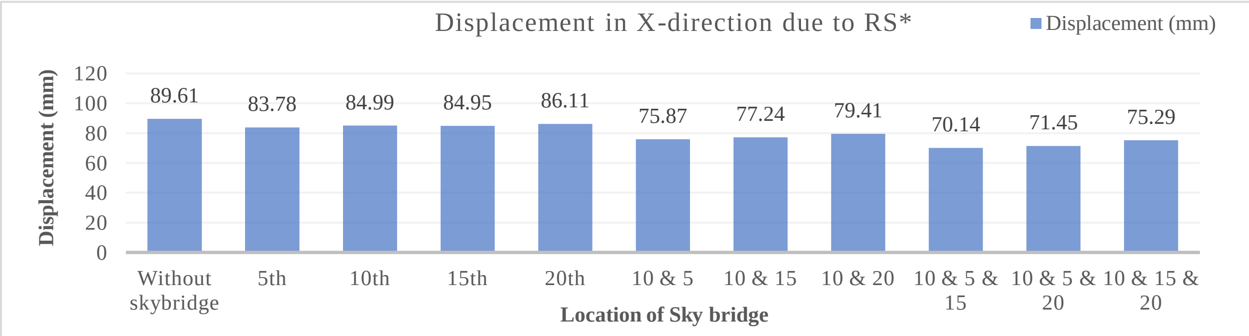

Figure 17 20 storey building Displacement in X-direction due to RS

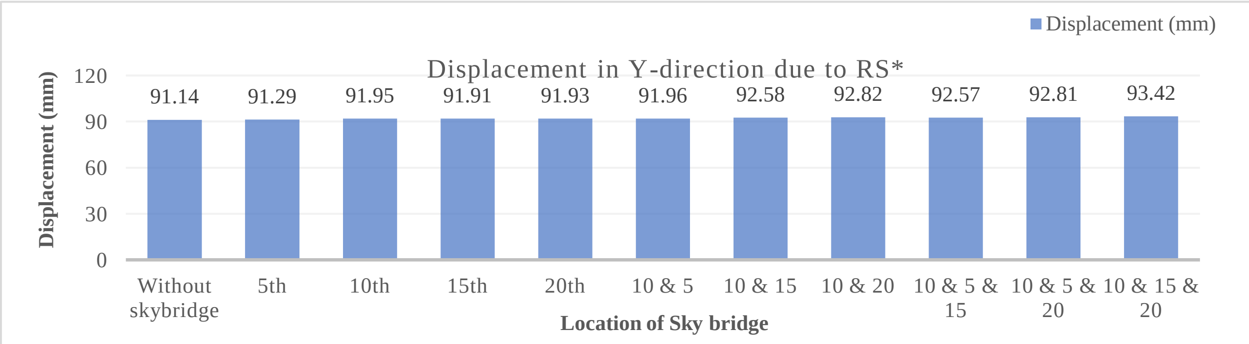

Figure 18 20 storey building Displacement in Y-direction due to RS

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*Response spectrum

As shown in above Figure, A 20-storey building with single skybridges on the 5th, 10th, 15th and 20th floors reduces displacement in the range of 13%, 20%, 18% and 14%, respectively, in the direction of the bridge.

A 20-storey building with Double sky bridges on the (10th & 5th), (10th & 15th) and (10th & 20th) floors reduces displacement in the range of 27%, 28% and 25%, respectively, in the direction of the bridge.

A 20-storey building with Triple sky bridges on the (10th & 5th & 15th), (10th & 5th & 20th) and (10th & 15th & 20th) floors reduces displacement in the range of 34%, 32% and 30%, respectively, in the direction of the bridge.

2) 20 storey building maximum storey drift

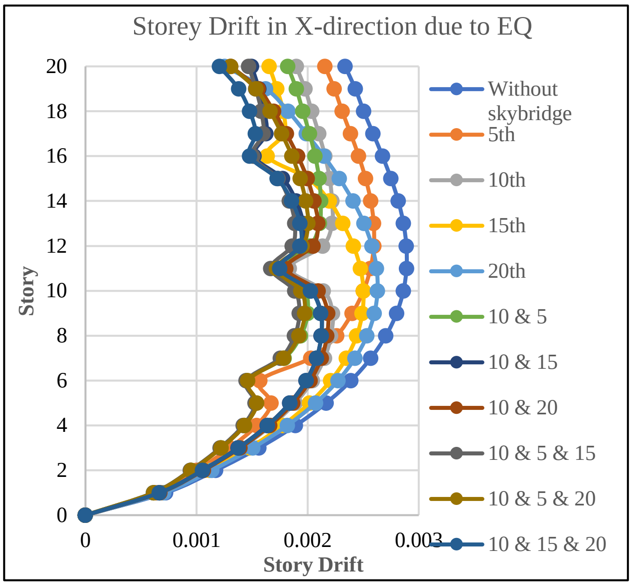

Figure 21 20 storey building Storey drift in X-direction due to EQ

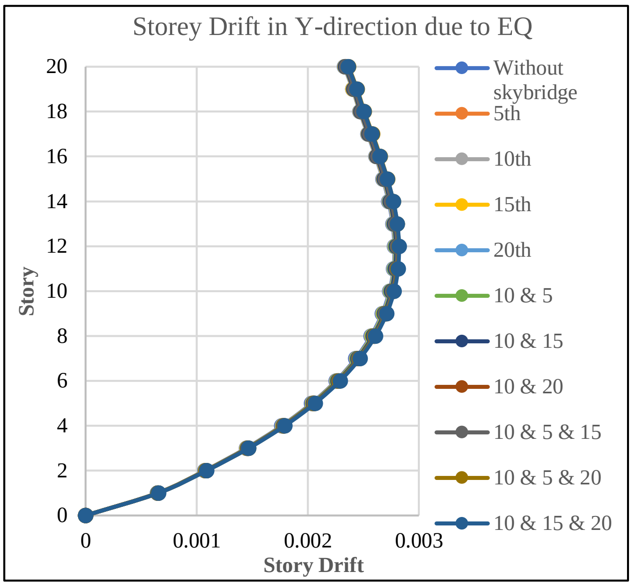

Figure 20 20 storey building Storey drift in Y-direction due to EQ

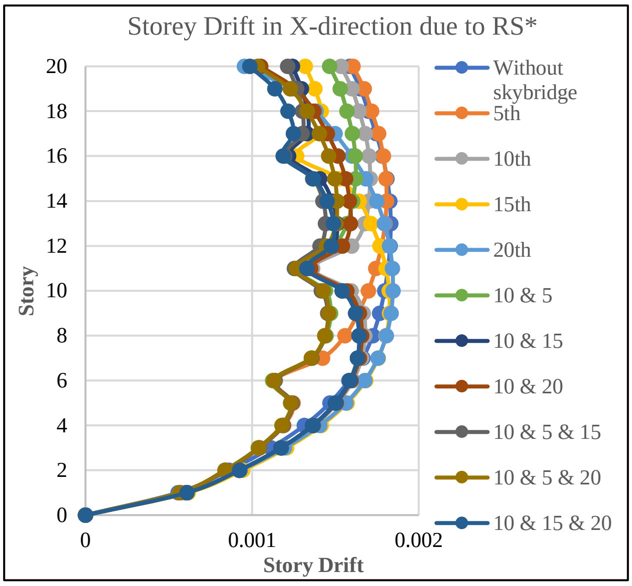

Figure 22 20 storey building Storey drift in X-direction due to RS

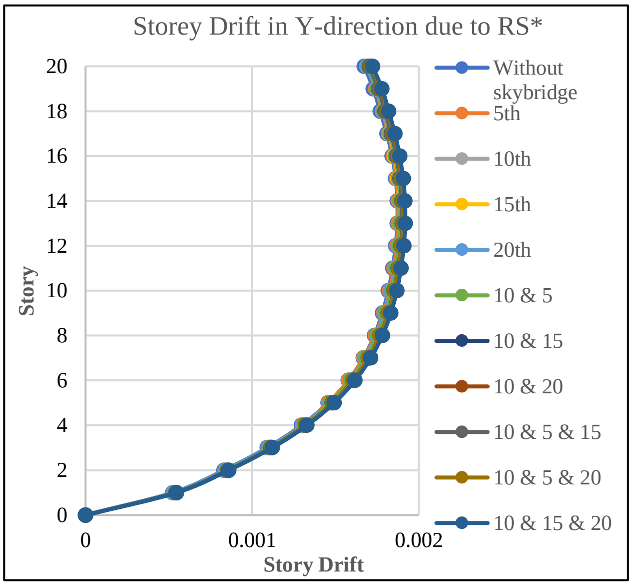

Figure 19 20 storey building Storey drift in Y-direction due to RS

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The maximum storey drift by adding sky bridges at different locations is shown in the above figure. It demonstrates that, in accordance with IS coddle provisions, storey drift is under control at less than 0.004. Additionally demonstrates that storey drift varies when force is applied to the bridge in that direction, but storey drift does not change when force is applied across the bridge.

*Response spectrum

3) 20 storey building Base shear

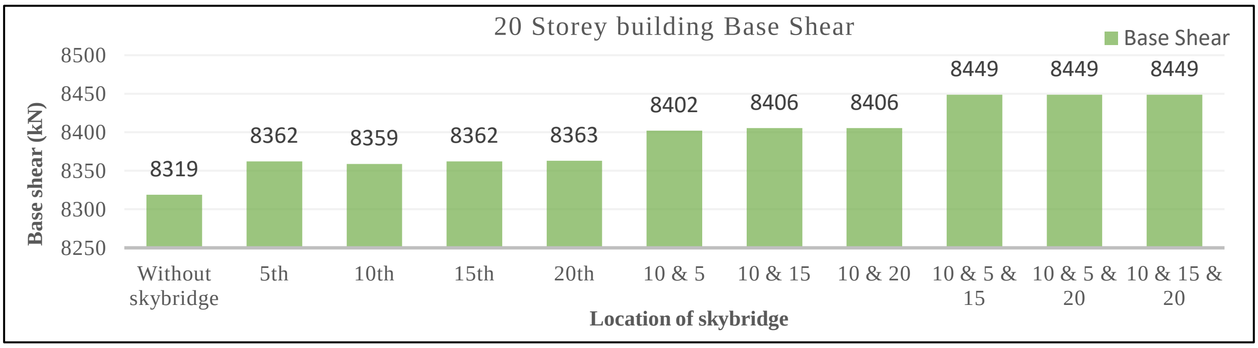

Figure 23 20 Storey building base shear of different models

C. 24 storey building results

1) 24 storey building maximum storey displacement

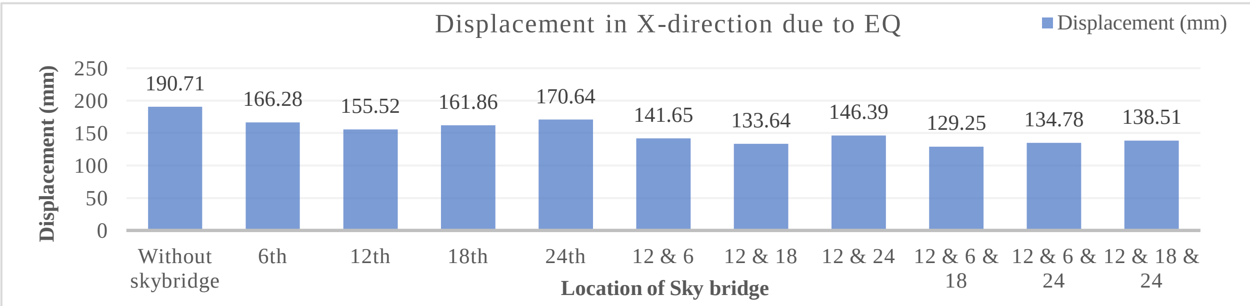

Figure 24 24 storey building Displacement in X-direction due to EQ

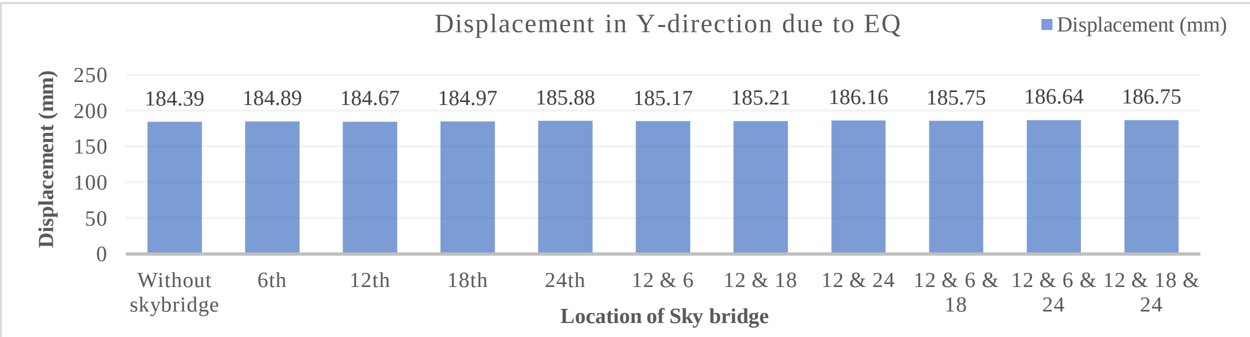

Figure 25 24 storey building Displacement in Y-direction due to EQ

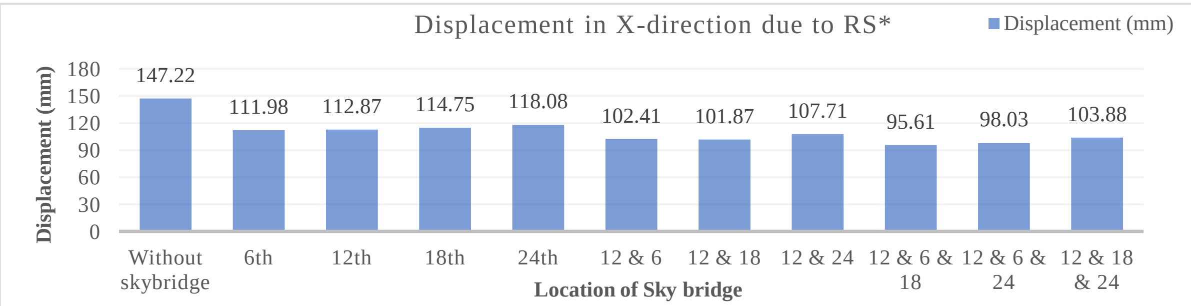

Figure 26 24 storey building Displacement in X-direction due to RS

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*Response spectrum

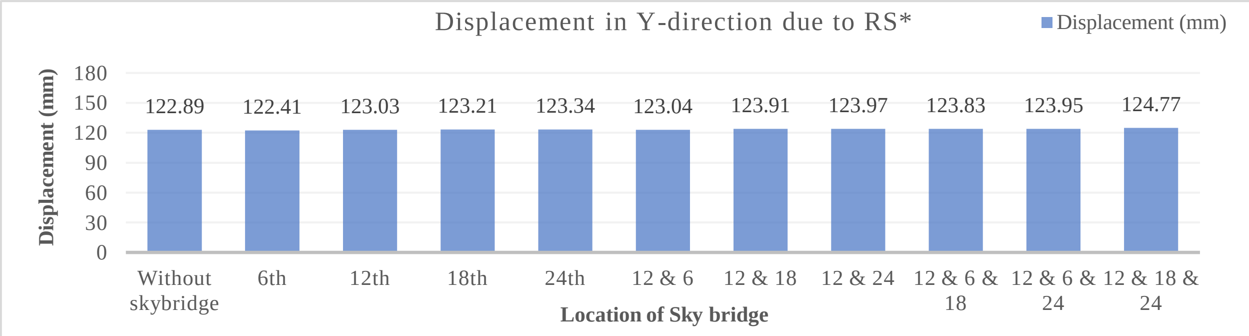


Figure 27 24 storey building Displacement in Y-direction due to RS

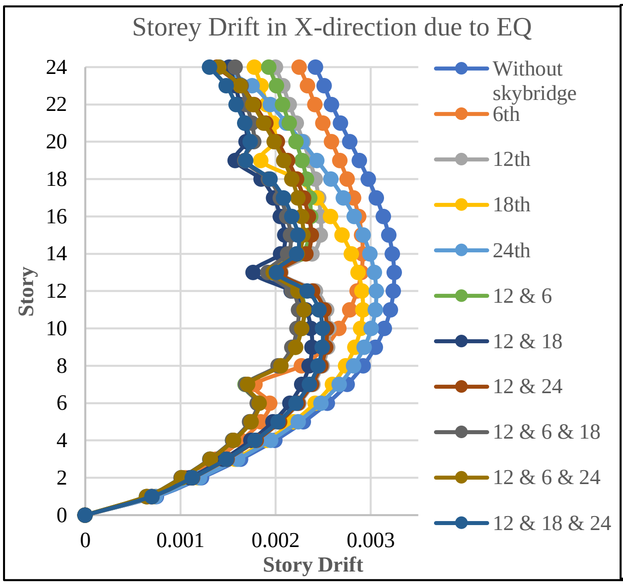
As shown in above Figure, A 24-storey building with single skybridges on the 6th, 12th, 18th and 24th floors reduces displacement in the range of 13%, 18%, 15% and 11%, respectively, in the direction of the bridge.

A 24-storey building with Double skybridges on the (12th & 6th), (12th & 18th) and (12th & 24th) floors reduces displacement in the range of 26%, 30% and 23%, respectively, in the direction of the bridge.

A 24-storey building with Triple skybridges on the (12th & 6th & 18th), (12th & 6th & 24th) and (12th & 18th & 24th) floors reduces displacement in the range of 32%, 29% and 27%, respectively, in the direction of the bridge.

The addition of single, double, and triple sky bridges to a 24-storey building reduces displacement in the direction of the sky bridge by about 18%, 29%, and 32%, respectively

2) 24 storey building maximum storey drift



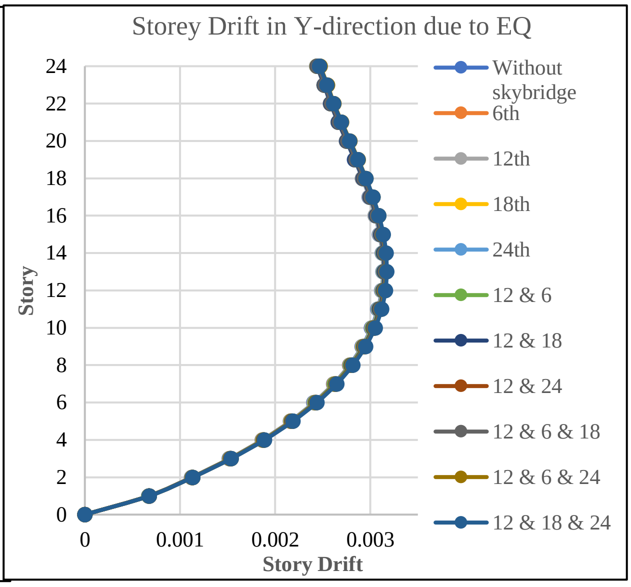


Figure 29 24 storey building Storey drift in X-direction due to EQ

Figure 28 24 storey building Storey drift in Y-direction due to EQ

The maximum storey drift by adding sky bridges at different locations is shown in the above Figure. It demonstrates that, in accordance with IS coddle provisions, storey drift is under control at less than 0.004. Additionally demonstrates that storey drift varies when force is applied to the bridge in that direction, but storey drift does not change when force is applied across the bridge

In all models, it is found that the model without the sky bridge has a higher story drift than the other model and in three sky bridges connected model has a lower storey drift than the other models of one sky bridge, two sky bridges and without sky bridge.

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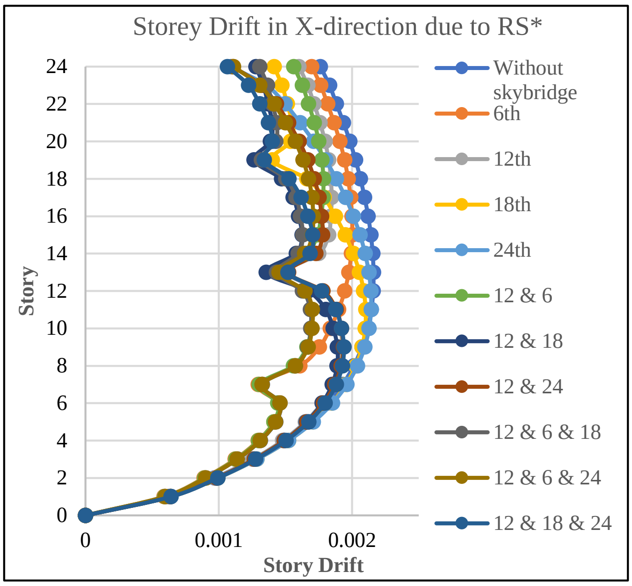

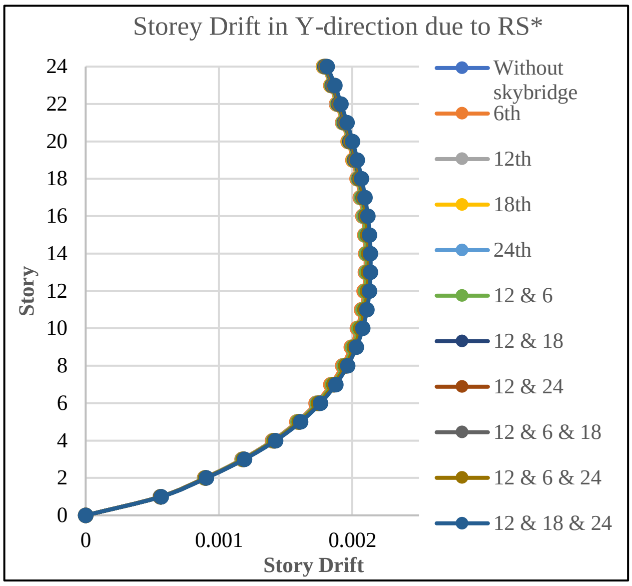

Figure 31 24 storey building Storey drift in Y-direction due to RS

Figure 30 24 storey building Storey drift in X-direction due to RS

3) 24 storey building Base shear

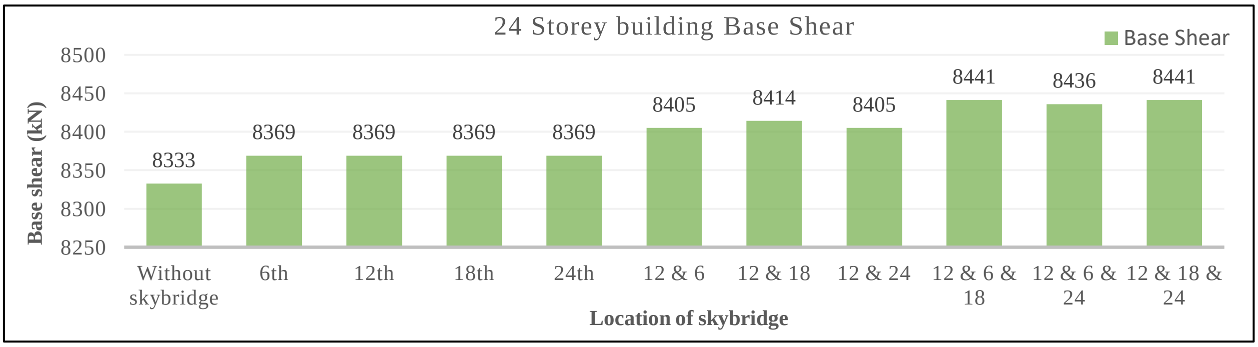

Figure 32 24 Storey building base shear of different models

D. 28 storey building results

1) 28 storey building maximum storey displacement

*Response spectrum

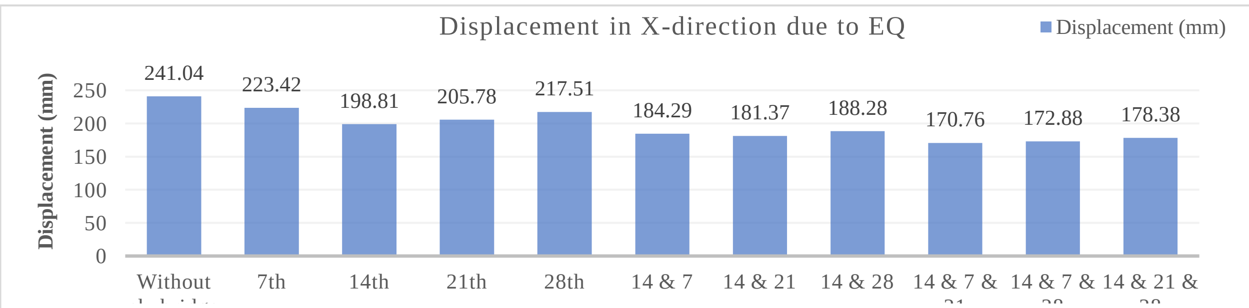

Figure 33 28 storey building Displacement in X-direction due to EQ

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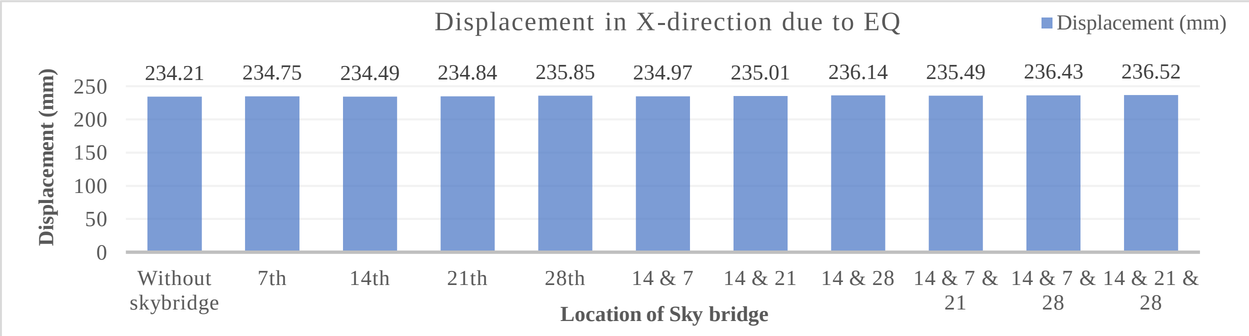

Figure 35 28 storey building Displacement in Y-direction due to EQ

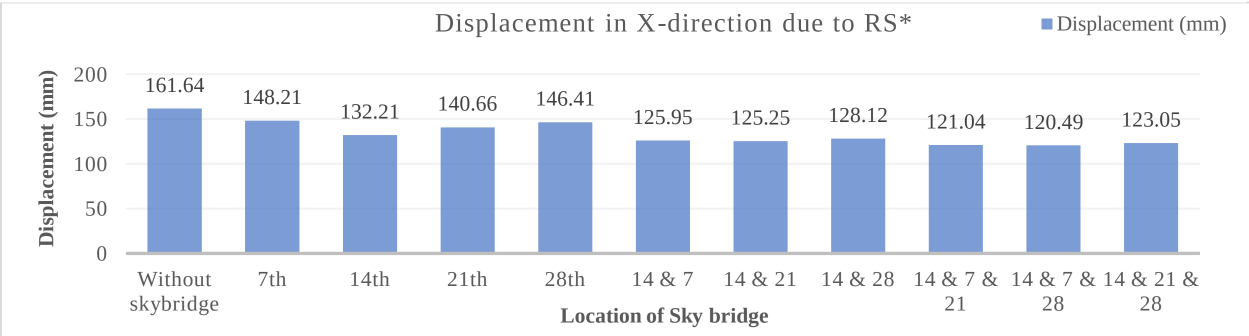

Figure 34 28 storey building Displacement in X-direction due to RS

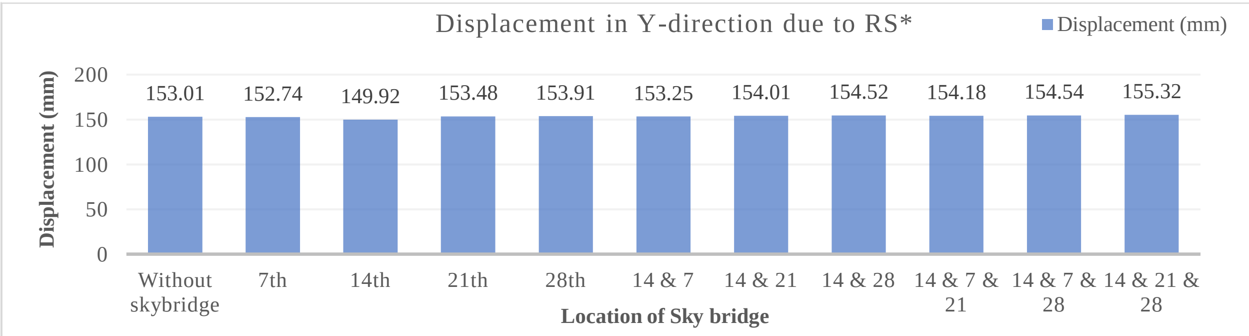

Figure 36 28 storey building Displacement in Y-direction due to RS

As shown in above Figure, A 28-storey building with single skybridges on the 7th, 14th, 21st and 28th floors reduces displacement in the range of 7%, 18%, 15% and 10%, respectively, in the direction of the bridge.

A 28-storey building with Double skybridges on the (14th & 7th), (14th & 21st) and (14th & 28th) floors reduces displacement in the range of 24%, 25% and 22%, respectively, in the direction of the bridge.

A 28-storey building with Triple skybridges on the (14th & 7th & 21st), (14th & 7th & 28th) and (14th & 21st & 28th) floors reduces displacement by approximately 30%, 28% and 26%, respectively, in the direction of the bridge.

The addition of single, double, and triple skybridges to a 28-storey building reduces displacement in the direction of the skybridge by about 18%, 25%, and 30%, respectively.

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*Response spectrum

2) 28 storey building maximum storey drift

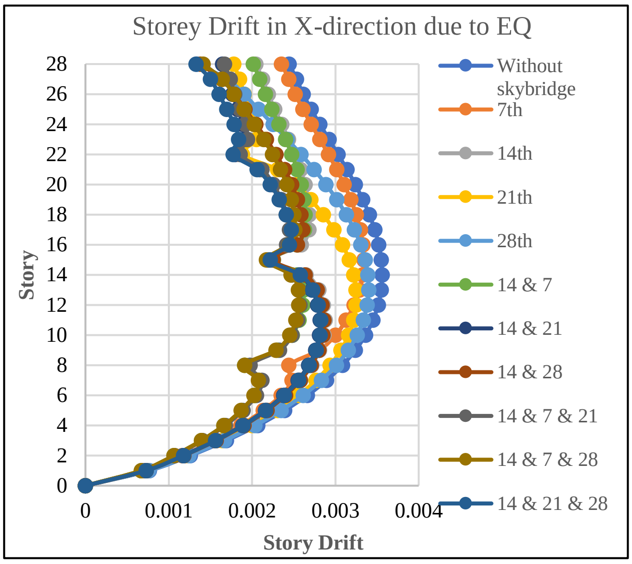

Figure 38 28 storey building Storey drift in X-direction due to EQ

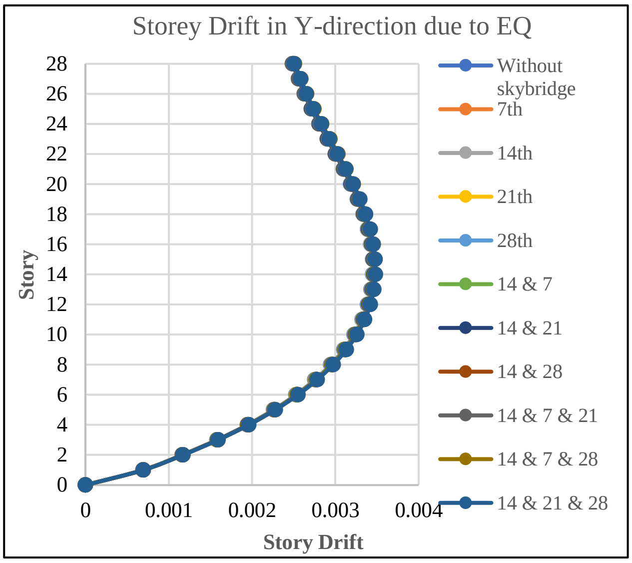

Figure 40 28 storey building Storey drift in Y-direction due to EQ

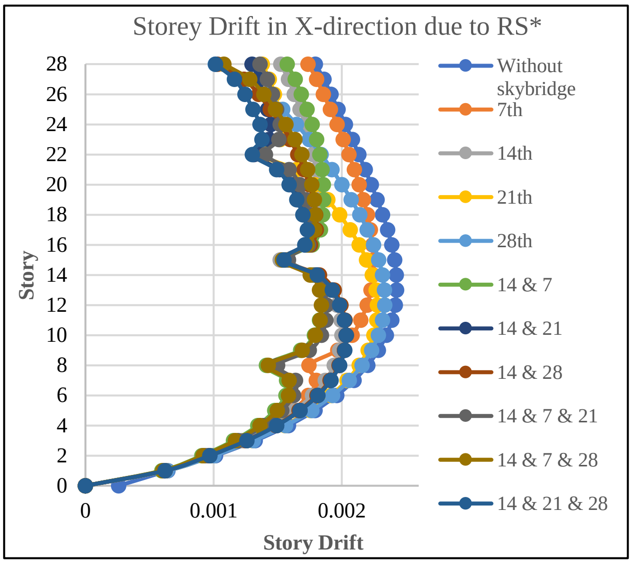

Figure 39 28 storey building Storey drift in X-direction due to RS

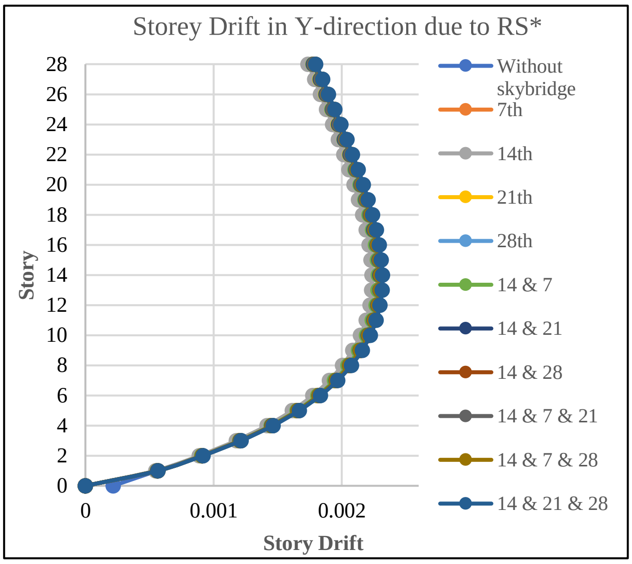

Figure 37 28 storey building Storey drift in Y-direction due to RS

The maximum storey drift by adding sky bridges at different locations is shown in the above Figure. It demonstrates that, in accordance with IS coddle provisions, storey drift is under control at less than 0.004. Additionally demonstrates that storey drift varies when force is applied to the bridge in that direction, but storey drift does not change when force is applied across the bridge

In all models, it is found that the model without the sky bridge has a higher story drift than the other model and in three sky bridges connected model has a lower storey drift than the other models of one sky bridge, two sky bridges and without sky bridge.

*Response spectrum

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3) 28 storey building Base shear

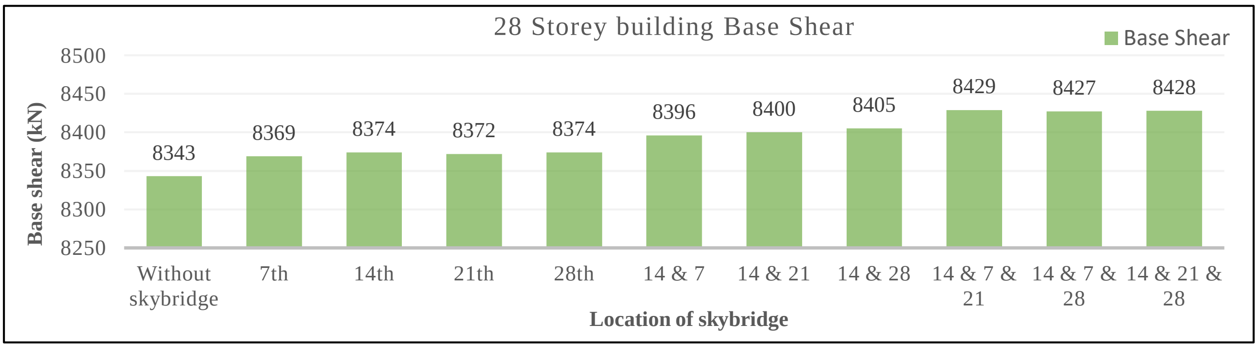

Figure 41 28 Storey building base shear of different models

V. CONCLUSION

- As the number of sky bridges in the building increases, displacement in the direction of the sky bridges decreases while there is no change in displacement in the across direction.
- Similar displacement patterns occur in buildings with different heights connected by sky bridges, where displacement along the bridge decreases while displacement along the across side does not change.
- This scenario is changes in the same floor height, when cross-sky bridges connect the two buildings, where displacement along the bridge remains constant, whereas displacement across side decreases noticeably.
- It is observed that the optimal number of sky bridges is 3 and that they should be located at the ($1/4^{th}$ & 1/2 & $3/4^{th}$) heights of the building.
- Result of this study it is observe by incorporating a sky bridge into a similar height 28-storey, 24-storey, or 20-storey building, displacement reduces by approximately 30%, 32%, and 35%, respectively.
- For the two sky bridges the optimum location at half (½) height of the building and the displacement reduces in the range of 25%, 29%, and 30%, respectively.
- For the single number sky bridge the optimum location at the (1/2 & $3/4^{th}$) height of the building and the displacement reduces in the range of 18%, 19%, and 20%, respectively.
- It is concluded that the displacement ratio also decreases with increasing building height.
- Result of this study is observed by incorporating a sky bridge into a different-height building displacement reduces by approximately 32%.
- In different height buildings connected by a sky bridge it is observed that displacement reduces in the range of 32%.
- Similarly, as the number of sky bridges increases in buildings, the storey drift decreases compared to buildings with fewer bridges or no sky bridges. it is noted that storey drift especially at floors which are connected by sky bridge is lesser compared to another storey.
- For base shear it is observed that with the increasing number of sky bridges in the building base shear increases marginally.

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