RESEARCH ARTICLE OPEN ACCESS

Effect on Seismic Behaviour of Structurally connected Tall Buildings

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ABSTRACT
This paper deals with the seismic response of two high rise buildings of 117m and 93m respectively, 21.11m apart, structurally connected by means of single, double and triple horizontal and inclined sky-bridges. A total of 10 different cases are considered, in all cases the buildings are analysed using dynamic analysis method and the responses of the buildings are recorded. The response of the buildings to seismic excitation in terms of time period, maximum storey displacement, story drift, storey shear and base shear of both buildings have been compared. The results confirmed that cases with inclined sky-bridge is better at reducing maximum displacement for taller of the two building by 10-29% depending upon number of sky bridges used while horizontal bridge is better at reducing maximum displacement for shorter of the two building by up to 10% depending upon number of sky bridges used. The combination of both horizontal and inclined sky-bridge resulted in reduction in displacement by 29% for taller building and a slightly increase by 4% for shorter building as compared to single horizontal sky-bridge.
Keywords - Horizontal truss connecting buildings, seismic analysis, Sky-bridge, skyways, tall buildings.

Date of Submission: 04-09-2022 Date of Acceptance: 19-09-2022

I. INTRODUCTION

Sky Bridges are types of elevated walkways consisting of enclosed bridge between two or more buildings usually in an urban area. In many scenarios they usually connect rail stations or other transport with their own footbridges and run many kilometres. Skyways are generally connected on the initial floors above the ground-level floor, but sometimes they are much higher like in Petronas Towers, Malaysia. The gap in the structures connected by sky bridges is usually devoted to retail business, so areas around the skyway may operate as a shopping mall. Non-commercial areas with closely associated structures, such as university campuses or hospital blocks many times have sky bridges between buildings.

The sky bridges must be correctly connected to the leading structure. There are three types of connections that are currently in use throughout the world. These include roller, hinge and rigid connections. The sky bridges connecting the three 42-storey towers in Island Tower Sky Club in Fukuoka City, Japan is an example of hinge connected sky bridges. 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 Telangana police headquarters located in Banjara Hills, Hyderabad is also one such illustration. The sky bridge in Shanghai World Financial Center in Shanghai, China is an example of rigid connections. Many examples can be found for rigid-connected sky bridges all over the world but examples of hinge-connected sky bridges are rare. Sky-Bridges can be connected at first few floors above the ground-level floor or at mid height, or near top floors or at roof level, or any combination of these. The position and support connection of Sky-Bridges have a large impact on the response of structures to vibrations, also, the effect of Sky-Bridge varies depending on the size and shape of the buildings. Multiple Sky-Bridges can be can be connected simultaneously which influences the behaviour of the coupled structures. Therefore, their effects on structural behaviour and design are required to be understood in order to minimize the damage caused due to vibrations.

II. LITERATURE REVIEW

Qing et al (2020) worked on analyses and optimal design of shared tuned mass damper for twin towers linked by a sky corridor using flexible connections. Optimum parametric analysis was performed using the principle of reducing the displacements of both towers. The model was subjected to El Centro earthquake ground motion. The system consisting of sky corridor mass and flexible connecting elements had a tuning effect on the towers. The results showed better seismic reduction effect could be achieved if the connected towers had similar dynamic properties [1]. Sayed Mahmoud (2019) comprehensively evaluated the response of connected high-rise buildings under earthquake loads. The model consisted of twin buildings of 30 story tall. The two towers were connected by a 33.60 m-long RC-sky-bridge supported on the columns of both towers. The position of the horizontally connecting sky-bridge was varied. It was found that when the connecting bridge was placed at the top of the twin buildings, the highest displacements were lower than in the other scenarios. Contrary to displacements, the basal shearing forces were remarkably complex than at other sky-bridge location scenarios, regardless of loading direction and earthquake motion [2]. Wei et al (2019) considered an asymmetrical high- rise building composed of a 299.1- m- high tower and a 235.2- m- high tower, which are diagonally and rigidly connected by two steel truss systems with the maximum span of 65.43 m. A shaking table test of a 1/45 scaled model was conducted. The results show that the joining ties and rigid connection joints behave well during strong seismic excitations. The damages concentrate on the connecting floors, and the complete structural damage is slight [3]. Sun et al (2014) studied a simplified 3-DOF model of twin-tower structure linked by a sky-bridge. The Bridge is connected to towers with the help of viscoelastic dampers. The effects of linking parameters, i.e., linking stiffness and damping ratio, on the dynamic responses of the two structures connected by sky-bridge with viscoelastic dampers are investigated. The research results show that the linking parameters at each end of the sky-bridge interactively affect the responses of two towers. They cannot be reduced to the best amount simultaneously except for symmetrical towers. The higher the elevation position of the sky-bridge is, the better the seismic mitigation effectiveness can be obtained for both towers [4]. Ying et al (2011) conducted an experiment with a multi-tower connected building. The towers are connected with a truss on the top, the truss has a circular opening in the center. A 1:25 scaled model of the structure was tested on the shake table under minor, moderate, and major earthquake levels. The connecting truss and the rigid joints between the truss and towers worked very well to keep the two structures deform together under three earthquake levels, however, the stiffness reduction due to the existence of the round opening is obvious especially under the major earthquake level. The authors concluded that an opening in the truss will reduce the stiffness provided by the truss, the stiffness should be improved due to potential vertical acceleration during major earthquakes [5]. Xilin et al (2009) case studied on Shanghai International Design Center, it is a high-rise building with two towers of different heights linked by tie, and the structural system is composed of steel frame, covered concrete core wall and shear walls. The shaking table tests of the 1:15-scale structural model were conducted. The two towers, although of different structural style and height, behave fundamentally in phase, and the stiffness of the linking truss is capable of coordinating the two towers to resist lateral forces jointly even under major earthquakes [6].

Though much of the literature is available and many researchers have dealt with analysis to investigate the seismic behaviour of the structures with equal or unequal heights connected with horizontal Sky-Bridge and concluded that the linkage between Sky-Bridge and the building does influence the behaviour of the structure during earthquakes, with flexible connection needing addition dampers to help stabilize the structure while rigid connection needs strong truss to withstand additionally developed stresses. But there is no work has been done on buildings with unequal height connected with inclined Sky-Bridge. The present study fills that gap and investigates the comparative analysis of response of two structures with unequal heights connected with horizontal or inclined Sky-Bridge(s).

The aim of this study is to determine the influence of horizontal Sky-Bridge and inclined Sky-Bridge on seismic behaviour of R.C building and compare their results. In this paper, ten cases of G+38 and G+30 storey buildings are taken into consideration and the angle of inclination of inclined Sky-Bridge is taken as 30 degrees. The cases are divided into three groups based on number of bridges used for connection. The first case is buildings connected with single horizontal bridge at 15^{th} floor of both buildings the remaining cases are then compared with this case. Building A consist of Reinforced Concrete Shear Wall system and building B consist of Reinforced Concrete Special Moment Resisting Frame with Shear Wall system. The structures are evaluated in accordance with seismic code IS-1893:2016 using response spectrum analysis.

III. BUILDING MODELS

Two reinforced concrete framed buildings of G+38 storeys and G+30 storeys are considered, which are connected by a steel framed sky-bridge. The buildings are assumed to be located on firm ground and soil-structure interaction in not taken into account. The two building towers are connected with a single inclined or horizonal Sky-Bridge and analysed, then number of Sky-Bridges is doubled and analysis is carried out again, and lastly the buildings are connected with triple Sky-Bridges and the analysis is carried out.

Table 1: General Specifications of buildings

Parameter	Building A	Building B
Number of stories	G+38	G+30
Dimension in X direction	25 m	23.06 m
Dimension in Y direction	40.23 m	33.06 m
Total height	117 m	93 m
Single storey height	3 m	3 m
Slab Thickness	150 mm	150 mm
Shear Wall Thickness	350 mm	350 mm
Beam size (in mm)	230 x 450 230 x 530	230 x 450 230 x 530
Column size (in mm)	---	500 x 1000
Grade of concrete for beams and slab	M30	
Grade of concrete for columns and shear wall	M60	
Grade of steel for RC work	Fe500	

The angle of inclination of Sky-Bridge is 30 degrees for inclined Sky-Bridge. The buildings under consideration are 21.11 m apart, so the length of horizontal Sky-Bridge is 21.11 m and the length of inclined Sky-Bridge is 24.37 m, the height of Sky-Bridge is 3 m which is same as the floors of the two buildings. The buildings are 117 m and 93 m high respectively. The building models have been designed for the governing load combinations as per the Indian Standards and the sections arrived from the structural design and other specifications of the building models are shown in table 1. The specifications of the sky-bridge are represented in table 2.

Table 2: General Specifications of Sky-Bridge

Parameter	Value
Length of horizontal Sky-Bridge	21.11m
Length of inclined Sky-Bridge	24.37m
Angle of inclination	30 degrees
Width of the bridge	6.3m
Main Beam size	ISWB 600
Bracing and vertical member	ISLB 100
Grade of steel for steel work	Fe410

Table 3: Seismic analysis parameters

Parameter	Value
Code	IS 1893 (Part 1): 2016
Seismic Zone	V
Zone factor	0.36
Response Reduction Factor	5
Importance factor	1.2
Damping ratio	0.05
Soil Type	III

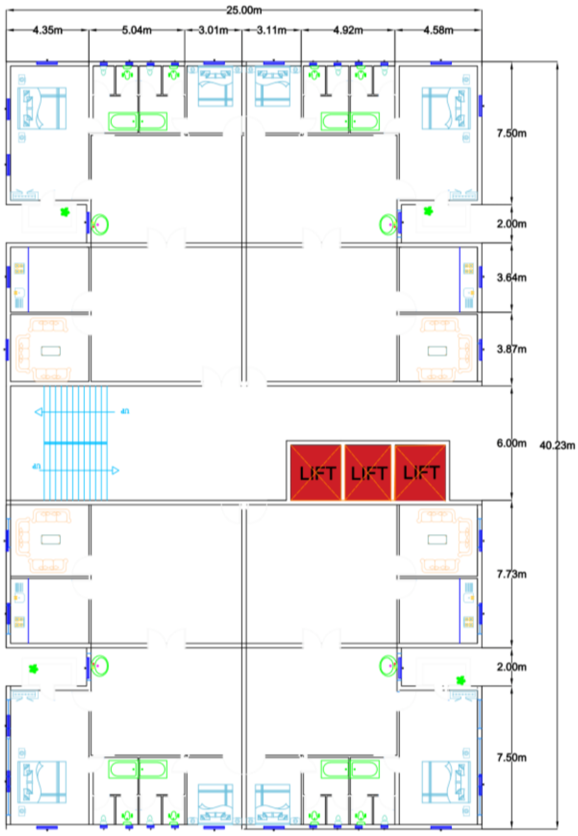

Figure 1: Architectural plan of building A

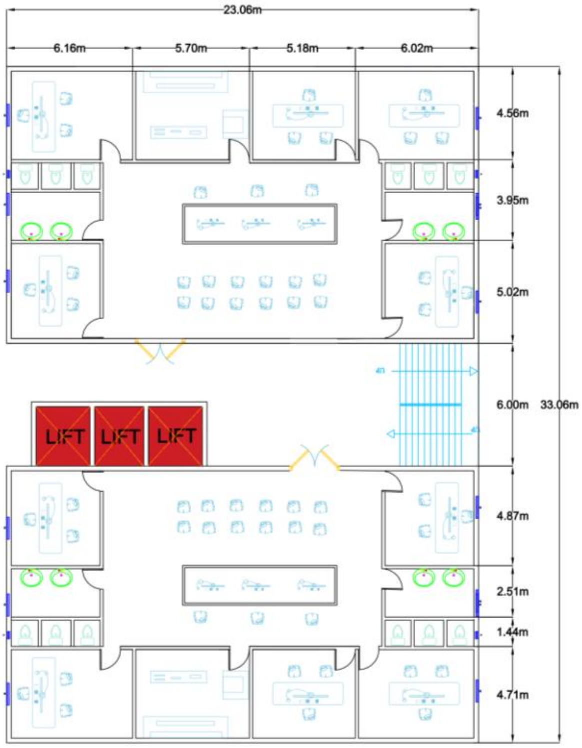

Figure 2: Architectural plan of building B

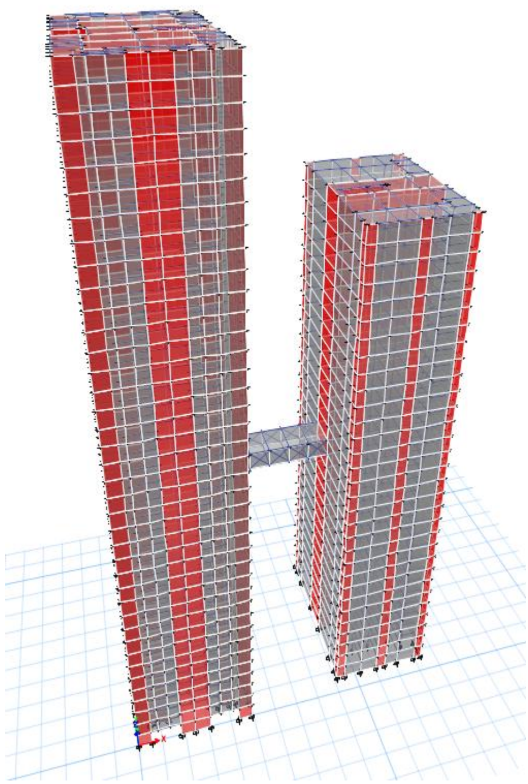

Figure 3: 3D Rendered View of the Model

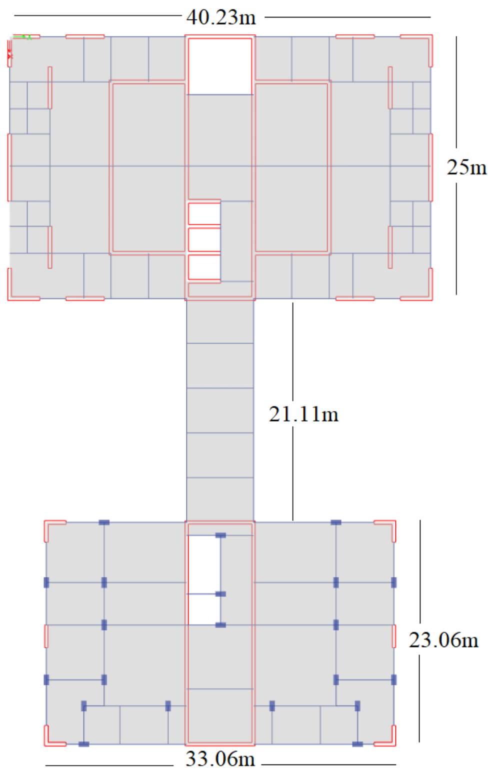

Figure 4: Plan of the Model

A live load of 3 kN/m^2 was considered for the buildings and 5 kN/m^2 for the sky-bridge. Concrete wall load was taken as 7.5 kN/m. Floor finish load was assumed to be 1.5 kN/m^2. The seismic analysis parameters considered are shown in Table 3. The structural analysis was carried out using the software SAP2000, considering the Indian Standard Codal provisions. The Figures 1 and 2 represent the architectural plan of the building models A and B respectively. Figure 3 and 4 represent the 3D rendered view of the model and the plan view of the towers connected by sky-bridge respectively.

As shown in Table 4, a total of 10 cases are considered which are divided into 3 groups and the results of each group cases are compared separately. The Figure 5, 6, and 7 give the pictorial representation of the cases considered.

Table 4: Cases Under Consideration

Group	Case	Type	Connecting storey of building A	Connecting storey of building B
A	1	Horizontal	15th	15th
	2	Horizontal	31st	31st
	3	Inclined	35th	31st
B	4	Horizontal	15th	15th
		Horizontal	31st	31st
	5	Horizontal	10th	10th
		Horizontal	31st	31st
	6	Inclined	19th	15th
		Inclined	35th	31st
	7	Inclined	11th	15th
		Inclined	35th	31st
C	8	Horizontal	31st	31st
		Horizontal	20th	20th
		Horizontal	10th	10th
	9	Inclined	35th	31st
		Inclined	24th	20th
		Inclined	14th	10th
	10	Inclined	35th	31st
		Horizontal	20th	20th
		Inclined	6th	10th

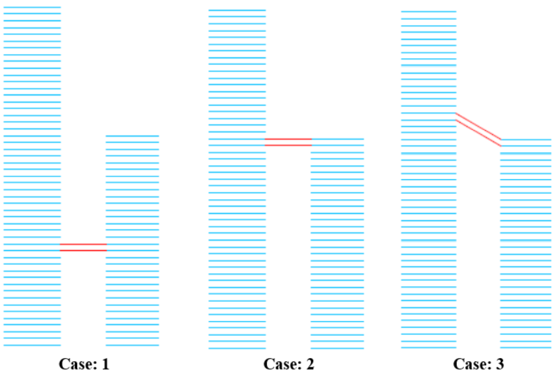

Figure 5: Building Models of Group A

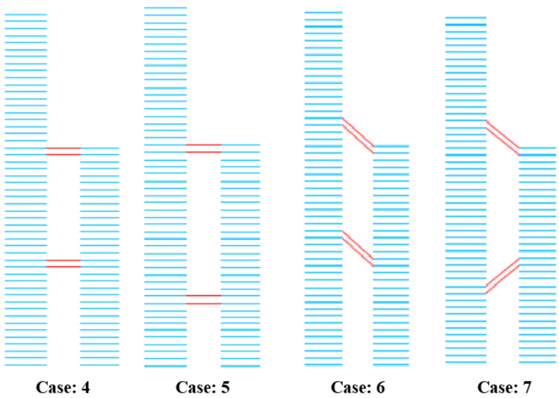

Figure 6: Building Models of Group B

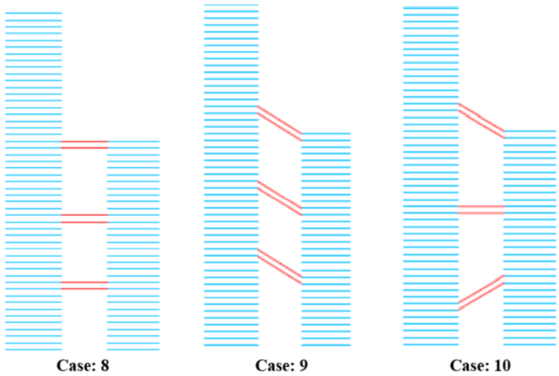

Figure 7: Building Models of Group C

The cases show that the sky-bridge is connected at certain elevation in horizontal and inclined manner, it acts as a linkage between high rise buildings to reduce lateral sway.

Case 1: A horizontal Sky-Bridge connects the buildings at 15th floor.

Case 2: A horizontal Sky-Bridge connects the buildings at 31st floor.

Case 3: An inclined Sky-Bridge connects the buildings from 31st floor of building B to 35th floor of building A.

Case 4: 2 horizontal Sky-Bridges located at 15th and 31st respectively floors connect the buildings.

Case 5: 2 horizontal Sky-Bridges located at 10th and 31st respectively floors connect the buildings.

Case 6: 2 inclined Sky-Bridges connect the buildings from 31st and 15th floors of building B to 35th 19th floors of building A respectively.

Case 7: 2 inclined Sky-Bridges connect the buildings from 31st and 15th floors of building B to 35th 11th floors of building A respectively.

Case 8: 3 horizontal Sky-Bridges located at 10th, 20th and 31st respectively floors connect the buildings.

Case 9: 3 inclined Sky-Bridges connect the buildings from 10th, 20th and 31st floors of building B to 15th, 23rd and 35th floors of building A respectively.

Case 10: 2 inclined Sky-Bridges connect the buildings from 10th and 31st floors of building B to 15thand 35th floors of building A respectively. An Additional horizontal Sky-Bridge connect both buildings at 20th floor.

IV. RESULTS AND DISCUSSIONS

4.1 Time Period

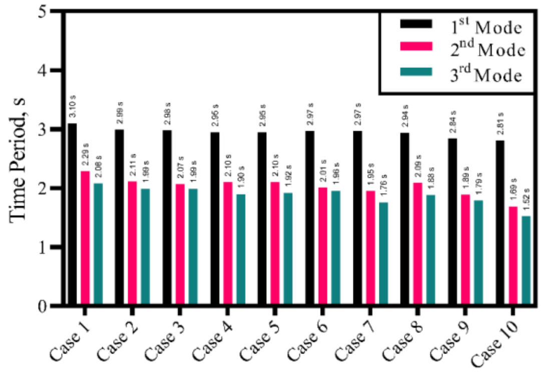

Figure 8: Time periods of first 3 modes

The time periods were chosen so as to attain a modal load participation factor of 90%, however only the first 3 periods are compared as shown in Fig. 8. It can be seen that the Case 1 which has single sky-bridge has the maximum time period among all the cases considered. As the number of sky-bridges increase the time period of the structure decreases.

4.2 Maximum Displacement

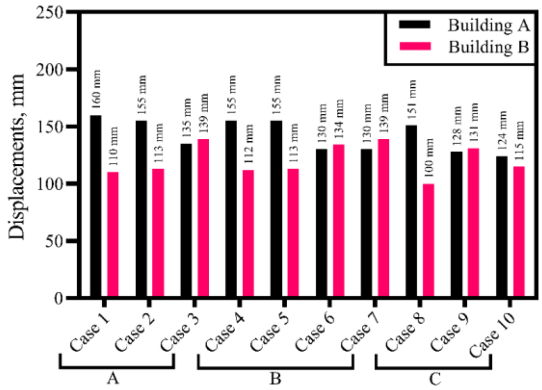

Figure 9: Maximum displacement in X direction

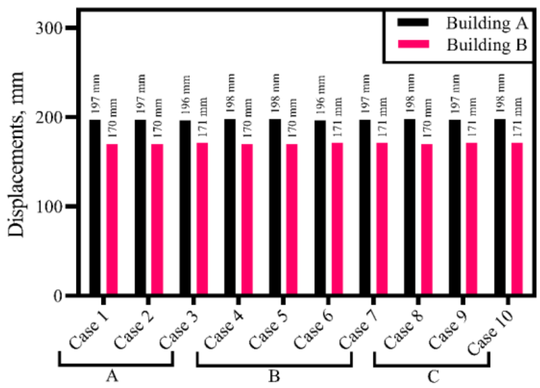

Figure 10: Maximum Displacement in Y direction for all cases

It can be seen from Fig. 9 that for Group A, the maximum displacement for building A decreases in case 3 by 16.6% and the maximum displacement of building B increases by 26.3%. Case 3 consist of single inclined Sky-Bridge connecting 31st floor of building B to 35th floor of building A. For Group B, the maximum displacement for building A decreases in case 6 and 7 by 19.7% and the maximum displacement of building B increases by 26.3%, all the cases in group B are connected by two Sky-Bridges. For Group C, were all the cases are connected by three Sky-Bridges, it can be seen that the maximum displacement for building A decreases in case 8 by 6% and 10% for building B, in case 9 it decreases by 20% for building A and increases by 19% for building B. Case 10 with two inclined and one horizontal Sky-Bridge shows decrease in maximum displacement for building A by 23% and increase by 4% for building B. It can also be seen from that maximum displacement decreases as the number of sky-bridges increases, also, horizontal sky-bridge benefits building B and inclined sky-bridge benefits building A.

From Fig. 10 it can observed that there is little to no variation in displacement in Y direction as Y direction is not affected by Sky-Bridge. Of all the cases, Case 10 seems to be well balanced with lowest displacement for building A (about 23% decrease) and slight increase in displacement (up to 4%) for building B. This is due to the two bridges are inclined with one facing up and other facing down, the distance between the top floors of building A and the Sky-Bridge reduces which increases the resistance to motion in the top floor as a result they displace less.

4.3 Storey Drift

Storey drift of G+38 R.C building is evaluated with different conditions cases of Sky-Bridge(s). It can be seen from Fig. 11 that the storey drift has similar pattern for Case 1 and 2, whereas for Case 3 it increases up to 30th floor and then suddenly reduces by 23% in X direction. This is caused due to the provision of inclined sky-bridge. It can be seen from Fig. 12 that there is no variation in storey drift in all cases due to the fact that the sky-bridge mainly affects the direction in which it is connected. Therefore, all the results in the subsequent sections are reported for X direction only.

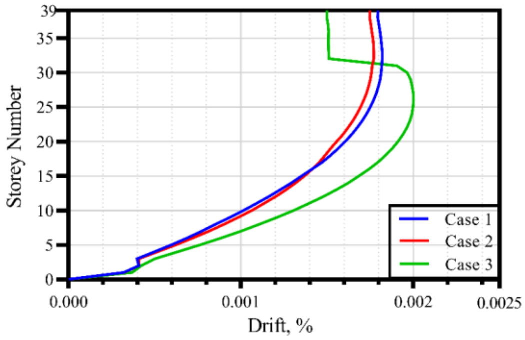

Figure 11: Storey Drift in X direction for group A

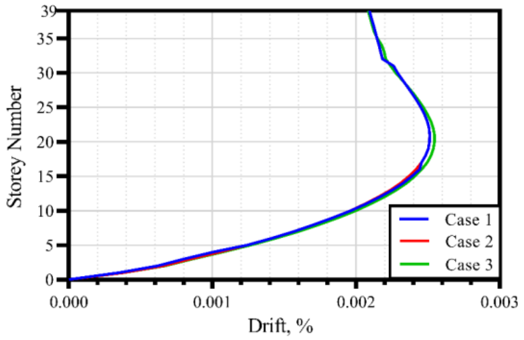

Figure 12: Storey Drift in Y direction for group A

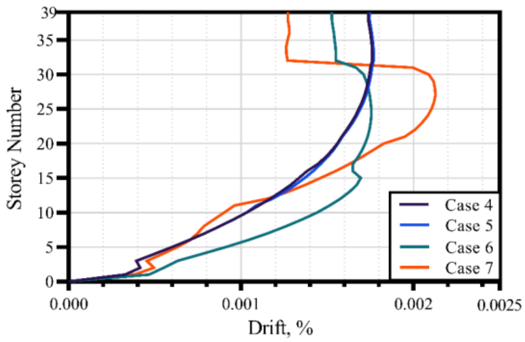

Figure 13: Storey Drift in X direction for group B

It can be seen from Fig. 13 that there is sudden reduction by 34.5% in storey drift around floors connected with inclined Sky-Bridge in Case 6 and Case 7, while there is little to no variation in Case 4 and 5 where horizontal Sky-Bridge is used.

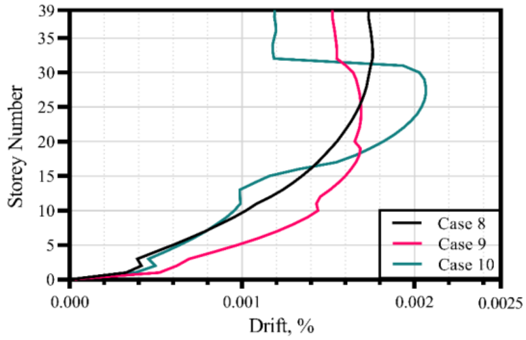

Figure 14: Storey Drift in X direction for group C

It can be seen from Fig. 14 there is sudden reduction by 35% in storey drift around floors connected with inclined Sky-Bridge in case 9 and case 10, while there is little to no variation in case 9 where only horizontal Sky-Bridge is used. There is a sudden variation in storey drift at stories on which Sky-Bridge is connected. In Case 2, 4 and 5 the storey drift decreases by 4-7%, this is due to the increase in the altitude of Sky-Bridge which increases the stiffness at the top floors. In Case 3 there is a drastic reduction in storey drift after 30th floor which is connected by an inclined Sky-Bridge. Also, the storey drift for each floor is comparatively less by 15% beyond 30th floor and is more below 30th floor. Similar pattern can be seen in Case 7 and 10 however the difference is the storey drift is even lower by 40%. It was found that the sudden reduction in drift is caused due to sudden increase in stiffness at floors where Sky-Bridge is connected.

4.4 Storey Shear

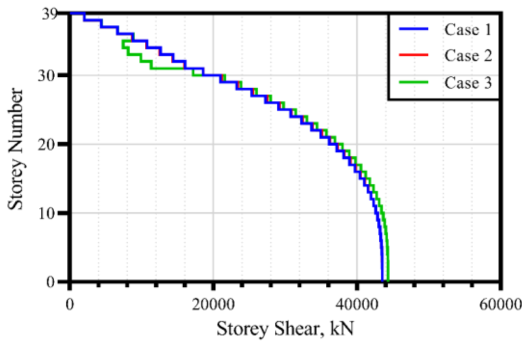

Figure 15: Storey Shear in X direction for group A

It can be seen from Fig. 15 that there is reduction in storey shear by about 34% in case 3 on floors where in an inclined Sky-Bridge is used as compared to case 1 and 2 where horizontal Sky-Bridges are used.

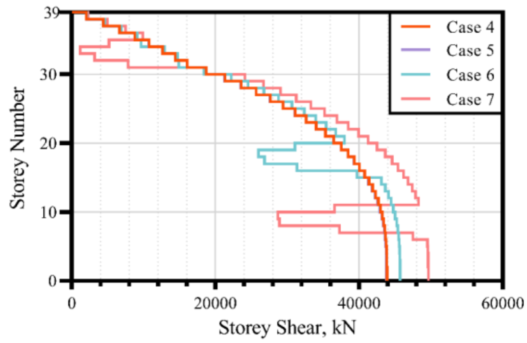

Figure 16: Storey Shear in X direction for group B

It can be seen from Fig. 16 that there is reduction in storey shear by about 41% in case 6 and 7 on floors where in an inclined Sky-Bridge is used as compared to case 1 where horizontal Sky-Bridge are used, however storey shear is more on floors below 30th floor by 12%.

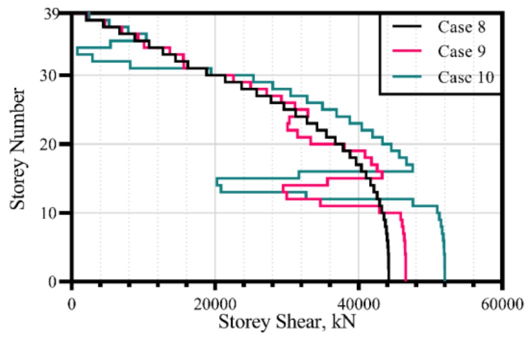

Figure 17: Storey Shear in X direction for group C

It can be seen from Fig. 17 that there is reduction in storey shear by about 45% in case 9 and 10 on floors where in an inclined Sky-Bridge is used as compared to case 1 where horizontal Sky-Bridge are used, however storey shear is more on floors below 30th floor by 17%. It is found that Case 1, 2 and 5 have similar storey shear this is because in all of these cases only horizontal Sky-Bridge is used for connection. Whenever an inclined Sky-Bridge is used, there is a sudden decrease and then sudden increase in storey shear but the overall storey shear is more than that of horizontal Sky-Bridge, like in Case 10, the maximum storey shear is 18% more than case 1 where only a horizontal Sky-Bridge is used. As the number of sky-bridges increases so does the mass of the structures which leads to higher storey shear and base shear.

4.5 Base Shear

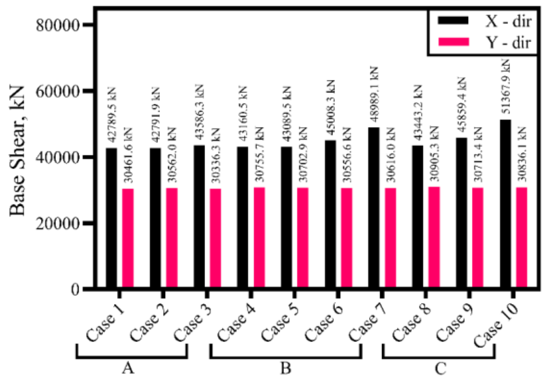

Figure 18: Base shear for all cases

It can be seen from Fig. 18 that there is slight increase in base shear in Case 3 by 2%, in Case 7 the base shear increases by 14.5% and for Case 10 the increment is 20.1%. Reduction in displacement makes structure stiffer which ultimately leads to increment in base shear.

V. CONCLUSIONS

The following conclusions are drawn from the analysis conducted in this paper:

- When inclined sky-bridge is used as connection the storey shear seems to increase by 10-15% and there is sudden decrease (up to 40%) and sudden increase in the storey shear on floors used for connection.
- Inclined sky-bridge is capable of reducing storey drift up to 35% if more than one sky-bridge is used. Horizontal sky-bridge is capable of reducing storey drift up to 5-7% if multiple of them are used.
- Base shear was found to be slightly higher (by 5-10%) whenever inclined sky-bridge(s) was used. However, it can decrease maximum displacement (up to 23%) for building A but it increases slightly for building B (up to 4%).
- Use of multiple sky-bridges as compared to single sky-bridge seems to reduce maximum displacement further for both buildings. As discussed in the results, use of double sky-bridge reduces maximum displacement by 14% while triple reduces by 23%.
- Sky-bridge(s) mostly influence the response of the building only in the direction they are connected in as seen in the results there was only 1-2% variation in storey drift, storey shear and base shear in Y direction.

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