Analysis and Design of Skybridges connecting Tall Buildings – A case study

B. Kiriparan, B. Waduge, W. J. B.S. Fernando, P. Mendis

ABSTRACT

Skybridges between adjacent tall buildings are generally adopted to offer iconic features such as sky gardens, swimming pools, observation decks and other luxury amenities. Improved fire safety, horizontal connectivity for pedestrians and enhancement of structural performance under lateral loads due to coupling effects are considerable added advantages to the aesthetic superiority. Structural analysis and design of skybridges are paid special attention as tall buildings constantly sway in a random manner under action of wind and earthquake induced lateral loads. The connection configuration between towers and the bridge highly influence the behaviour and design consideration of both towers and skybridge. Although the rigidly connected link provides improved damping and better structural performance under lateral loads resulting from structural coupling effects, alteration in distribution of internal forces through the structural system has to be carefully studied. Members of the towers and skybridge have to be designed to withstand appropriate internal force demands. In contrast, an isolated connection allowing independent movement of skybridge from the towers is convenient for analysis since each structure can be treated separately. However, excessive relative movement of skybridge causing human discomfort is inevitable in that case. Further, special attention has to be paid in selection of suitable structural bearings such as elastomeric, friction pendulum, guided slide bearing or a customized combination to achieve intended isolation mechanism. Thus selection of most suitable configuration of the connectors is vital. In addition, aerodynamic performance of the bridge pertaining to stability and human comfort under different wind conditions has to be verified. Requirement of auxiliary damping devices to meet human comfort of the skybridge has to be investigated. This paper addresses such fundamental design considerations in detail through a case study of a skybridge connecting fifty storied twin towers, authors have designed. Insight for connection mechanism of links connecting high rise towers, analysis of linked tall buildings under lateral loads, design of viscous dampers to improve the performance of isolated skybridges and aerodynamic effects on skybridge design are discussed.

Keywords: *Skybridges, Linked tall buildings, Bearings, Viscous dampers, Structural coupling.*

1 INTRODUCTION

The increasing urbanization of the global population coupled with increased sustainability demands have led to a large increase of tall buildings, especially in densely populated cities. Due to the scarcity for land in the metropolitan cities more and more tall buildings are being built in close proximity. Hong-Kong, Singapore and Dubai are being prime examples for cities with closely spaced skyscrapers. Construction of such multiple towers located adjacent to each other within a development, can be noted in Sri Lanka's commercial capital Colombo as well.

When tall buildings are located in close proximity, the opportunity exists to connect these structures to create additional physical space. The interconnected structures may include, but not limited to podium structures, sky gardens, or as discussed in this paper, skybridges.

This paper intend to highlight various design considerations to be made in the analysis and design of a skybridge connecting tall buildings. A detailed literature survey among existing skybridges around the world is summarized. Finally, a practical application of these fundamentals is detailed through a case study of a skybridge connecting fifty storied twin towers, authors have designed.

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2. SIGNIFICANCE OF SKYBRIDGES

Skybridges are generally adopted to offer iconic features such as sky lounges, swimming pools, observation decks and other luxury amenities. The National Congress Complex of Brasilia in Brazil was the first modern building to have a skybridge between two towers at a height above ground (Wood, 2003)

Figure 1. First modern building with skybridge (National Congress Complex of Brasilia in Brazil)

In addition to the esthetic superiority, skybridges interconnecting skyscrapers provide several added advantages. A new way of transportation can be utilized, letting people walk across the city without touching the ground, using “streets in the sky” (Taraldsen, 2017). This increase walkability and reduce vertical transportation in tall buildings, ground level congestion, air pollution, noise, fossil fuel consumption, traffic accidents, even obesity and stress (Jean and Mccall, 2013). The Linked Hybrid in Beijing, China is an eight-tower 22-story complex connected with skybridges between each building as shown in Figure 2. These skybridges serve as means of transportation between each tower but in addition, each skybridge has its own unique function such as housing a swimming pool, a fitness room, a cafe, a gallery, auditorium and a mini salon (Holl, 2009).

Figure 2. Linked Hybrid in China (Holl, 2009)

Contribution of skybridges for horizontal connectivity is better achieved in link bridges connecting building clusters in central business district of Hong Kong as shown in Figure 3. A detailed discussion on planning the skybridges to link the congested cities can be found in Wood (2005) and (Kayali, 2014).

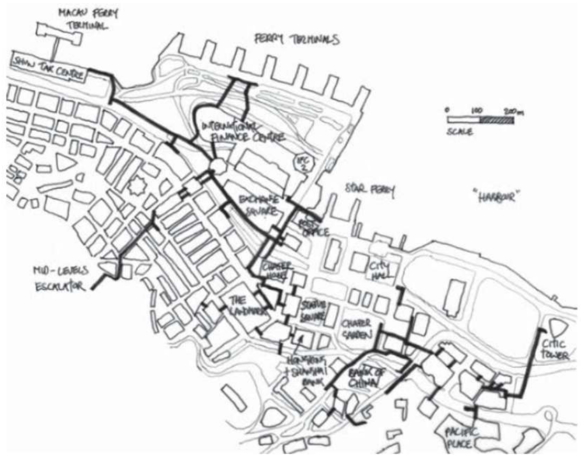


Figure 3. Extent of skybridge network in the central district of Hong Kong (Wood, 2011)

Skybridges can also save lives by providing multiple emergency escape routes for tall buildings subjected to fire or terrorist attack (NewScientist, 2006). A sky bridge can increase evacuation efficiency without increasing number of fire stairs. This advantage is well demonstrated in Petronas Tower in Kuala Lumpur, Malaysia (Wood, 2005). Figure 4 shows the contribution of skybridge in the evacuation plan of a single tower. A detailed discussion on planning skybridges for the evacuation strategy can be found elsewhere (Wood and Oldfield, 2007) and (Wood, 2011).

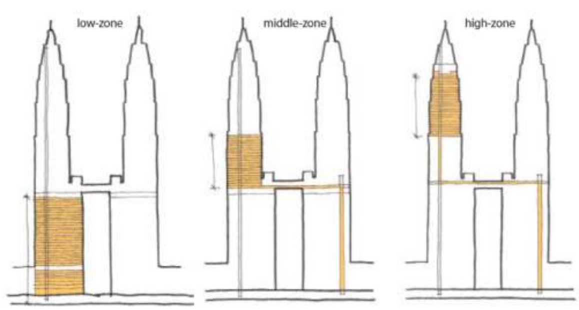


Figure 4: Use of the skybridge for different zones of the Petrona Tower for total evacuation of a single tower (Wood, 2011)

Further, Wood (2013) and (Safarik, 2019) underscores the need for skybridges, "It seems completely nonsensical that cities are making push for ever-denser, ever-taller urban form, but allowing only around plane to be the sole physical plane of connection". Considering these importance and value addition to the development, currently over 50 tall buildings around the world have incorporated skybridges (Wood, 2013).

3. STRUCTURAL CONSIDERATIONS OF SKYBRIDGES

Structural behavior of buildings linked through skybridges are altered, depending on their locations, stiffness, mass, and connection configuration with the buildings. Roller, Hinge and Rigid connections are three different type of connections configurations adopted. Roller or slider connections allow the skyscrapers to sway independently under lateral loading as shown in Figure 5(a). Axially stiff skybridges that are hinge-connected to the skyscrapers constrain the skyscrapers to sway in unison as shown in Figure 5(b). Flexurally stiff skybridges that are rigid-connected to the skyscrapers constrain the skyscrapers to deflect as a cantilever unit as shown in Figure 5(c).

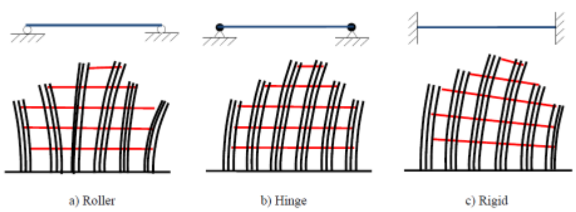


Figure 5. Roller, Hinge & Rigid-Connected Skybridges between Skyscrapers

The Gate of the Orient in Suzhou, China, shown in Figure 6, incorporates a rigidly connected arch that connects the top eight stories of the two towers, (Luong and Kwok 2012). Union Square in Hong Kong, is an 81-story tall residential skyscraper. It is made up of four separate towers called the Star, Sky, Sun and Moon towers. The Sun and Moon towers are connected at the 69th story and above, which forms the arch below (Wikipedia, 2013), as illustrated in Figure 7. The China Central Television Headquarters (CCTV) in Beijing, China shown in Figure 8 is another example of rigidly connected tall building. But its connecting "bridge" was designed much different than a typical bridge. It incorporated a combined system of a cantilevering overhang that connected 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 6. Gate of the Orient (SkyscraperCity, 2013)

Figure 7. Union Square - The Arch (Wikipedia, 2013)

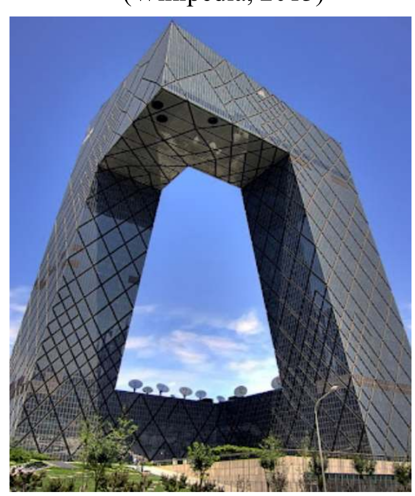
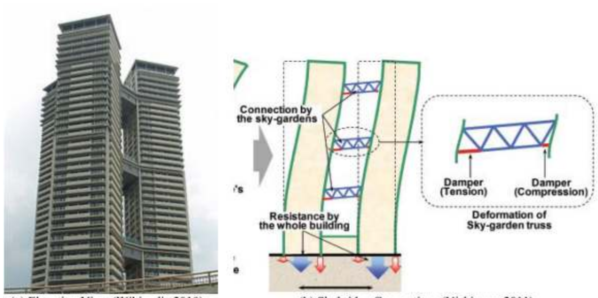


Figure 8. China Central Television Headquarters (Luong and Kwok, 2012)

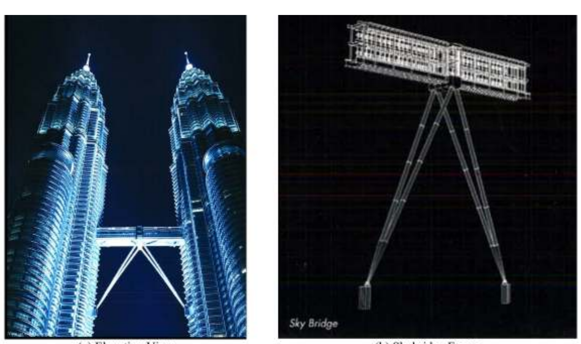
Island Tower Sky Club in Fukuoka City, Japan is a three 42-story apartment building shown in Figure 9 (Wikipedia 2010). The building towers have three-fold rotational symmetry. The towers are connected at the 15th, 26th and 37th stories by truss skybridges with hinged-joint. The lower part of the buildings are designed as one structural element with a continuous foundation. Each of the three towers have a core wall at the center of the plan with perimeter columns and connecting beams. The trusses are connected to the towers by vibration control dampers which decrease the overturning response to lateral loads. (Nishimura, 2011).



(a) Elevation View (Wikipedia 2010) (b) Skybridge Connections (Nishimura 2011)

Figure 9. Island Tower Sky Club

One of the most prominent examples of a roller-connected skybridge is the Petronas Towers in Kuala Lumpur, Malaysia shown in Figure 10. Twin 88-story office towers are connected at 41st story with a skybridge. The main bridge is a two-level steel frame with large beams and columns that connect to continuous girders. The girders are connected to the two towers with roller bearings, allowing the two towers to sway or twist independently of each other. The skybridge has an inverted V-shaped, two-hinged arch that supports the bridge mid span. The main bridge girders have a rotational pin directly over the arch allowing the bridge to rise and fall as the towers move closer or further apart (Abada, 2004).



(a) Elevation View (b) Skybridge Frame

Figure 10. Petronas Towers (Abada, 2004)

Figure 11 shows two 49 and 42 stories concrete residential buildings constructed in Seoul, Korea with a sky-bridge at the 34th story. The length of the long side of the sky-bridge is 15 m, and that of the short side is 10 m. The main structural system of towers against lateral forces is comprised of an internal core and belt walls at the 34th story. The lower stories of the 42- and 49-story buildings, i.e. below the 8th story, are merged into a single structure as shown in Figure 11. A conventional steel universal beam type bridge system is adopted for the skybridge structural system. A detailed investigation of dynamic performance of these towers under lateral loading and connector configurations are reported in (Lee, 2012)

Figure 11. Tower in Seoul, Korea (Abada, 2004)

Representative cases selected from existing sky bridges around the world are presented above for the enlightenment. Based on a detailed literature survey conducted following important points relevant to the structural design of skybridges can be summarized;

- Structural system of a skybridge to be selected based on the span, to resist the gravity loading and depending on the stiffness requirement if structural coupling between towers is required.
- Generally, skybridges with less stiffness (only consist of one or two stories) are roller connected allowing freedom for independent lateral movement and twist.
- Hinged joints may be adopted when skybridge has adequate axial stiffness and a requirement for structural coupling exists for reasons such as improving the damping or lateral performance and preventing pounding if buildings are located very closely.
- Rigid connections are adopted when

skybridges consist of several stories with higher flexural stiffness or where rigid joints are required for the stability of the skybridge itself.

- Determination of connection mechanism and investigation of dynamic performance play a major role in the structural design of skybridges.

4. DYNAMIC PROPERTIES OF LINKED TALL BUILDINGS

Understanding the dynamic properties of the coupled tall buildings is vital, in order to predict the structural performance of such buildings under the lateral loading. Free vibration characteristics such as mode shapes, natural frequencies and modal mass participation ratios are altered when buildings are coupled through skybridges. Figure 12 shows the influence of rigid structural coupling in altering the mode shapes. These free vibration characteristics can be determined through different methods such as analytical models given in the design codes, symbolic computing methods (Richards, 2011) or more precisely from modal analysis with the aid of Finite Element based programs.

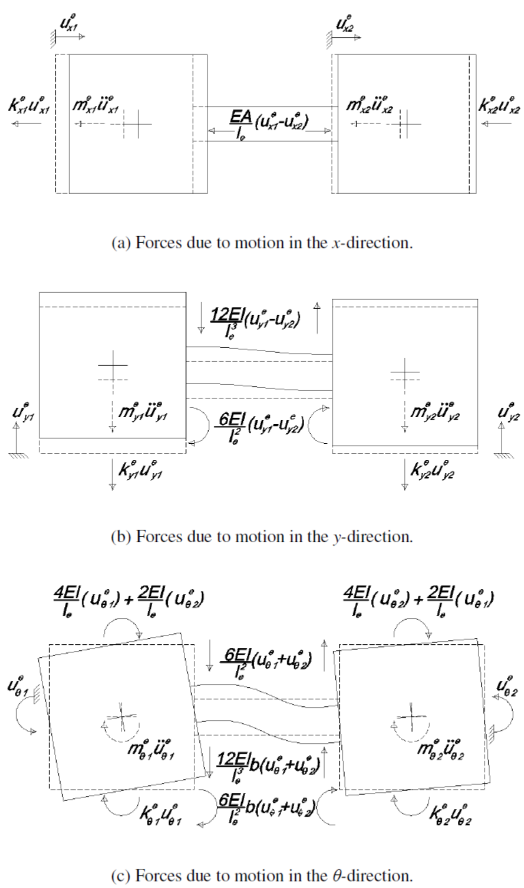


Figure 12. Coupling action due to motion in X, Y and θ directions (Richards, 2011)

Generally, it can be observed that, when tall buildings are coupled together, translational modes are combined with the torsional modes. Though the natural frequency is increased due to the coupling effect the torsional vibration modes and higher modes become dominant. Several detailed investigation on this effect were reported by both the researchers (Richards, 2011), (Jean and Mccall, 2013) and (Taraldsen, 2017) and designers (Wang, 2016). The location of link is another important factor which influences the coupling effect, a detailed description of which can be found elsewhere (Tse, 2013).

Further, when buildings are structurally coupled load distribution through the structural system is altered. A detailed investigation on the alteration of axial forces in the vertical elements of the towers can be found in (Acharya and Mathur, 2016)

5. BEHAVIOR OF LINKED TALL BUILDINGS UNDER LATERAL LOADINGS

Wind and earthquake are two primary lateral loading that governs design of tall buildings. When a dynamic load is applied to a structure depending on the dynamic properties of the structure it may dynamically respond. Dynamic response may amplify the structural responses compare to that obtained for equivalent static loads. The building's fundamental frequency of vibration, f_0, is most widely accepted property of a structure used to determine whether dynamic response will be significant under wind loading. The ASCE Standard [ASCE 7-10] classifies a structure as dynamically sensitive, or "flexible" if $f_0 < 1Hz$, otherwise it is considered to be "rigid."

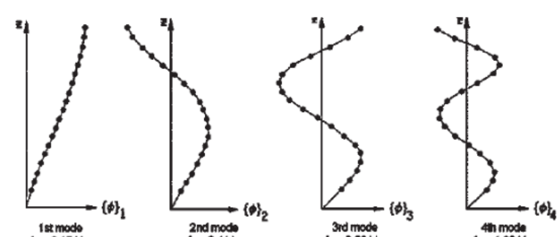


Figure 13. Typical shapes and frequencies of the first few modes for a 20 storied building structure (Boggs and Dragovich, 2006)

The first few modes and natural frequencies of a typical building are shown in Figure 13. The first mode is associated with the lowest frequency and smooth monotonic deformation; the higher modes feature increasing frequency and inflection points. The dominant frequency of wind gusts is relatively low compared to the lowest natural frequency of building structures, as shown in Figure 14, and primarily excites the lowest mode of vibration. This is in contrast to dynamic response to earthquakes, where the dominant excitation energy is in the frequency range of low-rise buildings or the higher modes of tall buildings. Hence, the alteration in dynamic properties of linked tall buildings due to coupling effect highly influence their performance under lateral loading.

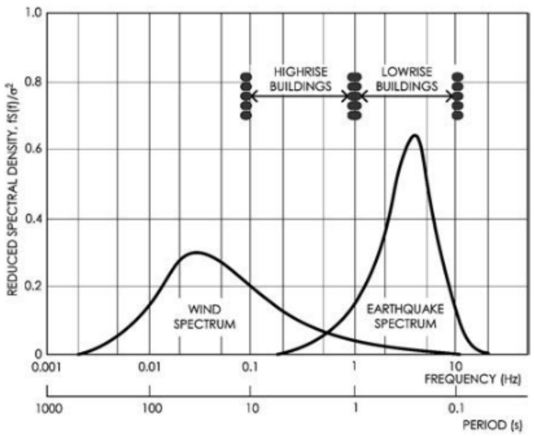


Figure 14. Frequency range of structures excited by wind and earthquakes (Boggs and Dragovich, 2006)

In this paper only wind induced effects on the structural design of skybridges are discussed in detailed.

5.1 Wind effects on design of linked tall buildings

Under the collective influence fluctuating wind action, a building tends to vibrate in rectilinear and torsional modes, as illustrated in Figure 15.

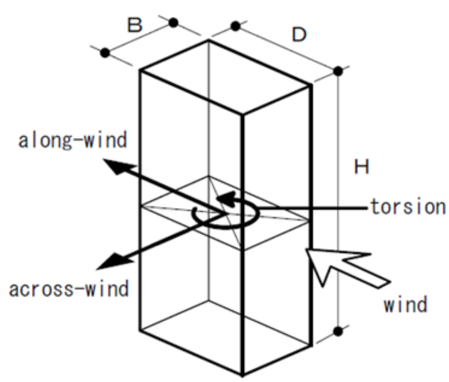


Figure 15. Wind effect on tall buildings

The amplitude of such oscillations is dependent on the nature of the aerodynamic forces and the dynamic characteristics of the building. Wind induced response of a tall building can be represented by equation (1)

$$\boldsymbol{X} - |H(f)|x \qquad \ldots(1)$$

Where x would be the displacement under static load, and X is the dynamic displacement. The character of mechanical admittance |H(f)| is illustrated in Figure 16. Importance of the effect of change in damping and free vibration frequencies during the coupling action again highlighted here.

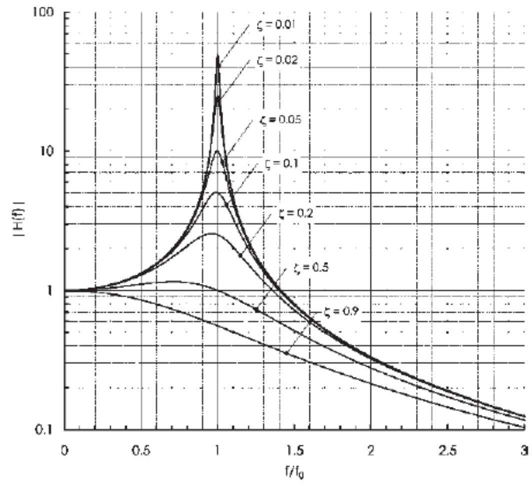


Figure 16. SDOF dynamic amplification factor.

Wind induced structural response of a tall building consist of Mean, background and resonance components as shown in Figure 17.

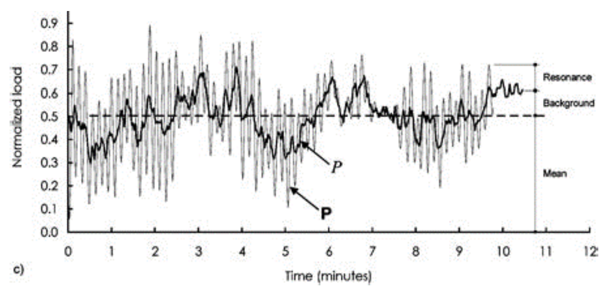


Figure 17. Sample wind excitation and responses (Boggs and Dragovich, 2006)

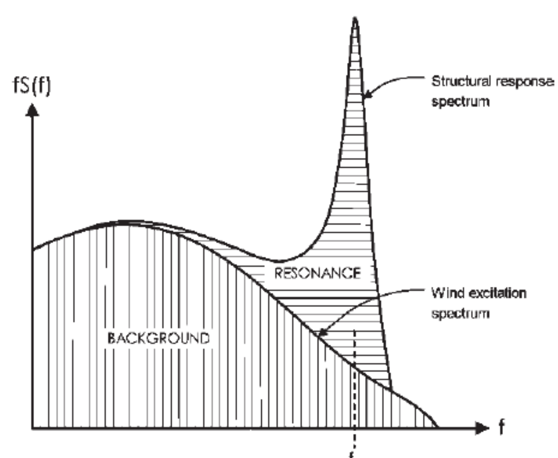


Figure 18. Background and resonance contributions to the response spectrum (Boggs and Dragovich, 2006)

Figure 18 shows the influence of dynamic properties of the tall buildings in the contribution of background and resonance responses.

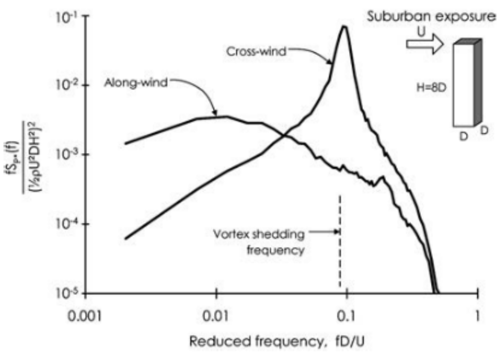
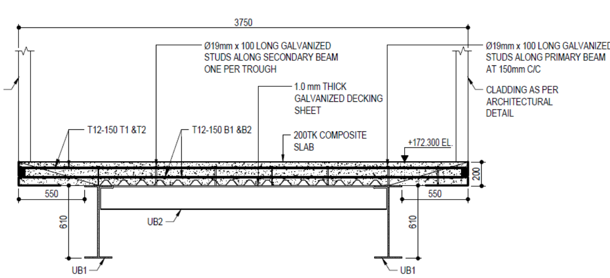


Figure 19. Aerodynamic load spectra measured on a wind-tunnel model (Boggs and Dragovich, 2006)

Aerodynamic load spectra from a wind tunnel shown in Figure 19, highlights importance of across wind loading due to vortex shedding. Sources of torsional wind loading and its importance can be found elsewhere (Boggs, Hosoya and Cochran, 2004) and (Holmes, Rofail and Aurelius, 2003). Further wind directionality, interference effects together with structural coupling gives great complexities in the wind design of coupled tall buildings. A detailed wind tunnel study can predict relevant design information for coupled tall buildings. Development of established methods such as high frequency force balance for coupled tall buildings are investigated by several researchers (Rofail and Holmes, 2007)

6. A CASE STUDY

A fifty storied twin towers proposed in Colombo, connected with a skybridge at roof top is shown in Figure 20. The proposed skybridge is located 172 m above the ground and spanning 10 m from one end of a tower to another tower.



21. cross section of the proposed bridge

Considering different factors described above (section 3 - 5) a conventional beam type bridge with steel girders and composite deck was proposed as shown in Figure 21.

Figure 20. Fifty storied twin towers connected with skybrige at roof top, located in Colombo, Sri Lanka.

Different connection configurations proposed for each four ends of the bridge main girder are shown in Figure 22. Based on the careful consideration of possible movements of each towers under lateral wind and earthquake loadings the proposed connection configurations were selected. Bridge is hinged at one position and allowed to slide in longitudinal directions when towers are moving in the longitudinal direction. The transverse movement and twisting of towers were accommodated by allowing the rotation of all the connectors in the plane of the bridge together with the specified longitudinal and transverse movements.
Different options such as elastomeric bearings, slide bearings and friction pendulum seismic isolation bearings were investigated for the connectors, to facilitate intended movements. Finally a customized guided slide bearings were selected as most suitable bearing type for the connection between skybridge and the towers.

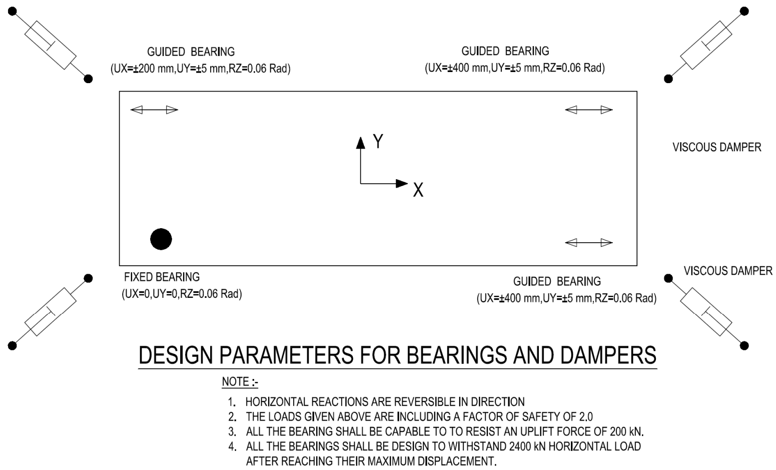


Figure 22: Skybridge connector configurations

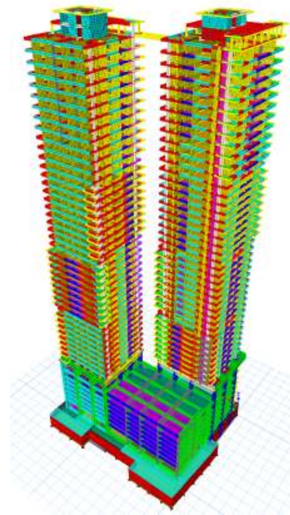


Figure 23: Finite element model of the twin towers with the skybridge

Further, due to the allowance of movement in all directions excessive relative movement between the towers and the bridge was observed from the analysis results. In order to control this excessive movement within the human comfort level a set of viscous dampers as shown in Figure 22 were proposed.

Allowable movements for each of these connections and performance of the dampers were determined from a finite element analysis carried-out. Figure 23 shows the finite element model of the proposed towers with the bridge. Here, link elements available in commercial purpose Finite element software "ETABS" and "SAP 2000" were utilized in modeling of the bearings and dampers. Time history and power spectral analysis were carried-out for wind and earthquake as appropriate.

The lateral movement of the tower at locations of proposed bearings, (as indicated in Figure 24) due to wind and earthquake in combination with the gravity loads, predicted from the analysis are shown in Table 1. Based on the analysis results shown in Table 1, required cumulative movement of bearings are summarized Table 2. Accordingly, design specification for bearings are developed and presented in Figure 22 and Table 4.

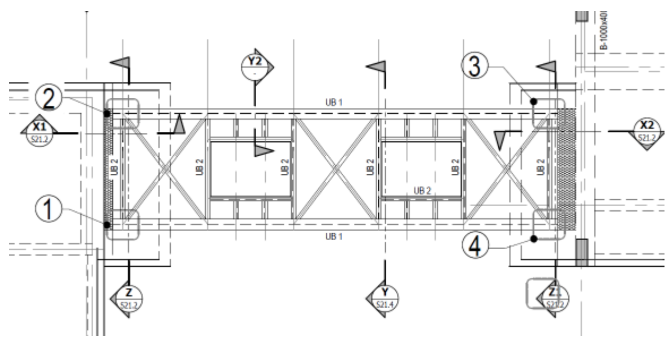


Figure 24: Key plan of the bridge indicating the proposed bearing locations

Table 2: Building displacement for rollers (mm)

(1+4)	Ux	370
	Uy	388
	Uz	14
(2+3)	Ux	370
	Uy	388
	Uz	14

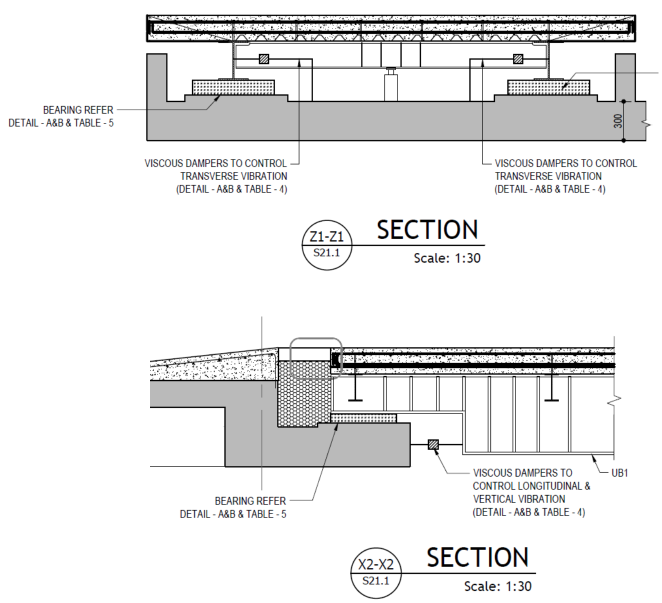


Figure 25: Sectional details of the connections

Table 1: Displacement of towers at bearing locations (mm)

LOCATION	DIRECTION	LOAD CASE				DESIGN DISPLACEMENT AT ONE END
		WIND X	WIND Y	EARTHQUAKE X	EARTHQUAKE Y	
1	UX	150	40	180	52	180
	UY	35	185	36	190	190
	UZ	6	4	5	6	6
2	UX	150	40	180	52	180
	UY	35	185	36	190	190
	UZ	6	4	5	6	6
3	UX	180	32	190	60	190
	UY	40	198	36	190	198
	UZ	8	3	6	8	8
4	UX	180	32	190	60	190
	UY	40	198	36	190	198
	UZ	8	3	6	8	8

ABBREVIATION
UX - LONGITUDINAL DISPLACEMENT
UY - TRANSVERSE DISPLACEMENT
UZ - VERTICAL DISPLACEMENT

Intended forces that bearing are subject to, at the maximum displacement, under different load cases are tabulated in Table 3.

Table 3: Bearing support reactions for maximum displacement

LOCATION	LOAD CASE	FORCE DIRECTION DIRECTION (kN)		
		HX	HY	V
1	DL+LL	0	0	500
2	DL+LL	0	0	500
3	DL+LL	0	0	500
4	DL+LL	0	0	500
1	DL+LL+WL	2400	650	500
2	DL+LL+WL	0	650	500
3	DL+LL+WL	0	650	500
4	DL+LL+WL	0	650	500

ABBREVIATION
DL - DEAD LOAD
LL - LIVE LOAD
WL - WIND LOAD

A summary of the specification developed for the bearings are summarized in Table 4.

Table 4: design parameters for customized guided slide bearings

VERTICAL BEARING CAPACITY (kN)	HORIZONTAL BEARING CAPACITY (kN)		MAXIMUM HORIZONTAL DEFORMATION CAPACITY (mm)		ROTATION CAPACITY (RAD)	QUANTITY OF BEARINGS
	LONGITUDINAL DIRECTION	TRANSVERSE DIRECTION	LONGITUDINAL DIRECTION	TRANSVERSE DIRECTION		
500	2400	650	-	-	± 0.06	1
500	2400	650	± 200	± 5	± 0.06	1
500	2400	650	± 400	± 5	± 0.06	2

NOTE :- 1. HORIZONTAL REACTIONS ARE REVERSIBLE IN DIRECTION
2. THE LOADS GIVEN ABOVE ARE INCLUDING A FACTOR OF SAFETY OF 2.0
3. ALL THE BEARING SHALL BE CAPABLE TO RESIST AN UPLIFT FORCE OF 200 kN.
4. ALL THE BEARINGS SHALL BE DESIGN TO WITHSTAND 2400 kN HORIZONTAL LOAD AFTER REACHING THEIR MAXIMUM DISPLACEMENT.

The design parameters of viscous dampers are summarized in Table 5 below.

Table 5: Design parameters of viscous dampers

HORIZONTAL DESIGN FORCE (kN)	DAMPING COEFFICIENT (C) (kN/m/s)	VELOCITY COEFFICIENT	MAXIMUM STROKE (mm)	DESIGN VELOCITY (m/s)	QUANTITY OF DAMPERS
200	500	0.2	± 400	0.01	4
200	500	0.2	± 200	0.01	1

6.1 Skybridge aerodynamics

Stability of the skybridges against aerodynamic behavior such as flutter and buffeting shall be ensured. The flutter is a coupled motion of translation and twisting of the bridge itself. Buffeting is a vertical or lateral vibration due to the shedding vortices as shown in Figure 26. The stability of the bridge against flutter is verified by keeping the two adjacent natural frequencies of the bridge at least 2.5 times apart. Buffeting performance is verified using the spectral density analysis methods. Power spectra proposed by Kaimal(1972) was used for along wind loading and spectra developed by Panofsky(1960) was utilized for the vertical vibration.

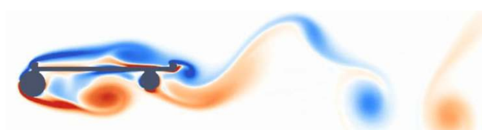


Figure 26: Possible formation of vortices around the bridge

In order to minimize the possible buffeting effects cladding profiling around the structural girders are developed based on the qualitative descriptions recommended as shown in Figure 27.

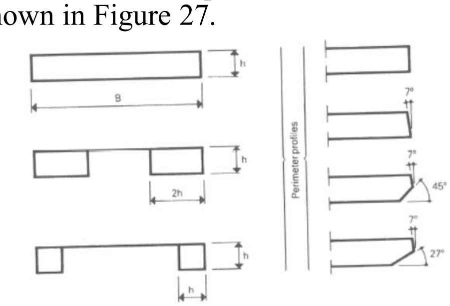


Figure 27: Qualitative description of bridge shapes for vortex shedding

7. CONCLUSION

This paper provides an overall insight for structural design and detailing of sky bridges. A detailed literature review of structural system, connector configurations and structural behavior of existing skybridges around the world are summarized. Further, a case study of skybridge connecting fifty storied twin towers, authors have designed, is discussed in detailed. Following important conclusions can be made from the investigations conducted.

- Connection configuration of Skybridges with the tower highly influence the dynamic properties of the towers and consequently it's performance under lateral loading.
- Roller connected skybridges are used when the stiffness of the bridge is comparatively less.
- Customized guided slide bearings are suitable for roller connected skybridges in low seismic zones.
- Appropriate movements to be accommodated and forces to be withstand by the bearings can be determined from Finite Element Analysis.
- A dynamic time history analysis or power spectral analysis can be used to analysis the linked tall buildings under the wind loading. Mean, Background and Resonance components of wind loading to be appropriately represented in the analysis, as the coupled tall buildings are more sensitive for dynamic response.
- Relative movement of skybridge is to be investigated in roller connected bridges. A set of properly placed viscous dampers can be used to control the excessive relative movement which may cause discomfort for the users.
- Frictional resistance from the bearings and introduction of viscous dampers may cause significant structural coupling, which may lead to the alteration of internal forces in the tower's structural members.
- Possibility for aerodynamic instabilities such as flutter and buffeting are very important. Proper profiling of bridge covering will help to reduce vortex shedding and subsequent buffeting.

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