10th International Conference on Structural Engineering and Construction Management (ICSECM)
12th – 14th December 2019 l Earl's Regency Hotel l Kandy l Sri Lanka
ISBN-978-955-589-273-5
ICSECM2019-130

STRUCTURAL CHALLENGES IN DESIGN AND DETAILING OF SKYBRIDGES CONNECTING TALL BUILDINGS

B. Kiriparan[1]*, B. Waduge [1], W. J. B. S. Fernando [1] and P. Mendis[2]
[1] *Civil and Structural Engineering Consultants (pvt)ltd, Sri Lanka.*
[2] *University of Melbourne, Australia.*
** Correspondence E-mail: kiriparan@csec.com.lk , TP: +94719922602*

Abstract: Implementation of skybridges between towers is becoming trendy these days in the urbanizing world to achieve smart mobility in addition to the aesthetic, spatial and technical concerns. Emerging new technologies and thoughts of architects made the bridge to build at the higher elevation which challenging the structural engineers. Predicting the dynamic behaviour of the skybridge under wind, earthquake and other lateral loadings are vital. Selection of structural system for the bridge, connection configuration, any damping solution if required are comprehensively discussed in this paper through a case study. The detailed methodology for design and detailing of a skybridge that connecting fifty storied twin towers is well formulated in this paper considering all the aspects that studied through the literature survey. A finite element model is utilized to perform the analysis for the linked tall buildings under lateral loadings most importantly under wind loadings. The roller connection is achieved by the customized guided slide bearings. Further, the viscous dampers are proposed as a supplementary solution to mitigate the excessive relative movements thus the human comfort is preserved. The authors have also addressed the aerodynamic stability of the skybridge in this study.

Keywords: Skybridges; Structural coupling; Bearings; Viscous damper; Aerodynamic stability

1. Introduction

In the new revolution of urban connectivity, the skybridges or skyways are being as a better solution than the past centuries due to smart mobility. The emerging new technologies and new thoughts make these skybridges built at high elevation together with more functional. Horizontal development through the skybridges is increasing in its popularity due to its improved interconnectivity between towers while having more and more added benefits beyond the aesthetic appearance. The basic idea of the skybridges are the people can move from one tower to another at the higher elevation by reducing the vertical circulation, ground level congestion, accidents and also the mental stress while saving time and fuel consumption.

When tall buildings that vibrates under lateral loadings are connected through skybridges many structural challenges to be addressed. As connected tall buildings are not frequently encountered by the designers only very limited number of literatures regarding the analysis and design of skybridges were found. This paper intend to highlight various design considerations to be made in the analysis and design of a skybridge connecting tall buildings.

2. Literature Survey

A detailed literature survey is as essential to guarantee the high quality and functionality of the skybridge going to be built. Important design aspects from selected skybridges around the world are presented here.

2.1 Significance of Skybridges

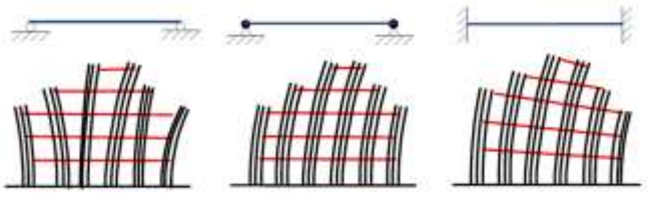
Beyond the aesthetic beneficial from the skybridges, it has some other added advantages for spatial, technical and mobility integration. It offers spatial benefits by providing additional amenities and services to the people. The SkyPark of Marina bay sands in Singapore is having a capacity of thousands of peoples to stay at the skybridge which is also facilitating the peoples with infinity pool, observation deck and landscaped gardens. And also, the Linked Hybrid complex in Beijing, China is a 220,000 square meter pedestrian oriented complex. Eight residential and hotel towers are interconnected by offering multifunctional skybridges including, swimming pool, fitness room, cafe etc...

The building services like mechanical systems and other utilities can be simply integrated across the towers through the skybridges. Also, the skybridges are providing easy horizontal evacuation from one tower to another in case of fire or any emergencies. Evacuation efficiency is well established in one of the famous towers in Southeast Asia, Petronas Tower in Kuala Lumpur, Malaysia (Wood, 2005).

2.2 Structural Considerations of Skybridges around the world

In addition to the aesthetic, spatial and technical considerations, the connectivity of towers via skybridges is also affecting the structural performance of the towers during the earthquake and wind excitations. The coupling control of the towers through the skybridges are altering the dynamic response of the towers significantly.

Connection configuration of the skybridge together with the connecting buildings is an important parameter that deciding the structural performance. The connection can be differentiated into three as roller, hinged and rigid connections depending on the internal forces exerted on the structures, which are demonstrated in Figure 1.



a) Roller b) Hinge c) Rigid

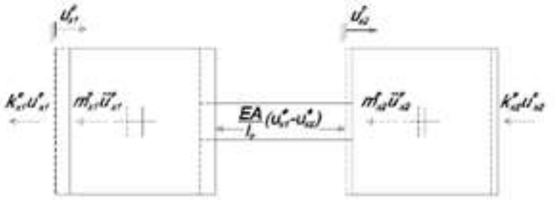
Figure 1: Different connection configuration and structural behaviour.

The Gate of Orient in Suzhou, China, Union Square in Hong Kong, and the China Central Television Headquarters (CCTV) in Beijing, China are some of the examples for the rigidly connected skyscrapers around the world. Rig-id connections were adopted for multi-storeyed skybridges which provides greater flexural rigidity. Island Tower Sky Club in Fukuoka City, Japan is an example of a truss skybridge connected with hinge joints and vibration control mechanism. Hinge jointed skybridges requires grater axial rigidity to transfer and resist axial forces induced due to the coupling action. Roller connection is adopted for the skybridge of Petronas Towers in Kuala Lumpur, Malaysia. Here, the twin towers are connected allowing the sway and twist of towers independent to each other by incorporating roller bearings (Abada, 2004). Roller connections are most suitable for bridges with less axial and flexural stiffnesses and each towers can perform satisfactory under lateral loadings whereas rigid and hinged connected skybridges will help to improve the lateral performance of the towers through coupling action.

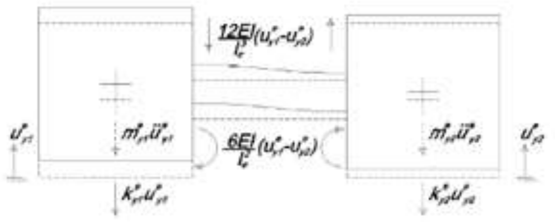
2.3 Study on the structural coupling of towers

Linking the tall buildings at the higher elevation is a challenging task in terms of its dynamic behavior. Unlike the isolated towers, the coupled towers show a different response to the lateral excitations due to its altered dynamic characteristics such as natural frequencies, modal mass and modal mass participation ratios. Figure 2 illustrates the alteration of mode shapes with the influence of rigid structural coupling.

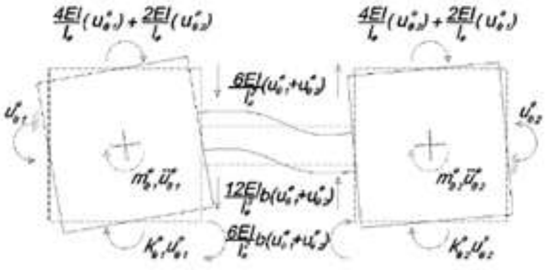
In terms of mode shapes, the torsional vibration mode and the other higher modes become dominant when coupling the towers together. Many researchers investigated this effect in detail during the past years (Richards, 2011, Amy, 2013 and Tormod, 2017 and Wang, 2016).



(a) Forces due to motion in the x-direction.



(b) Forces due to motion in the y-direction.



(c) Forces due to motion in the θ-direction.

Figure 2: Coupling action through rigidly connected link due to building motion in X, Y and θ directions. (Richards, 2011)

3. Characterization of Linked Tall Buildings Under Wind Loading

The governing design criteria for slender tall buildings are the response for the lateral loadings primarily wind and earthquake. As shown in Figure 3, the dominant frequencies of wind gusts are relatively low compared to the structures' lowest natural frequency while the dominant excitation frequency of the earthquakes falls in the range of low-rise buildings or the higher modes of the high rise buildings.

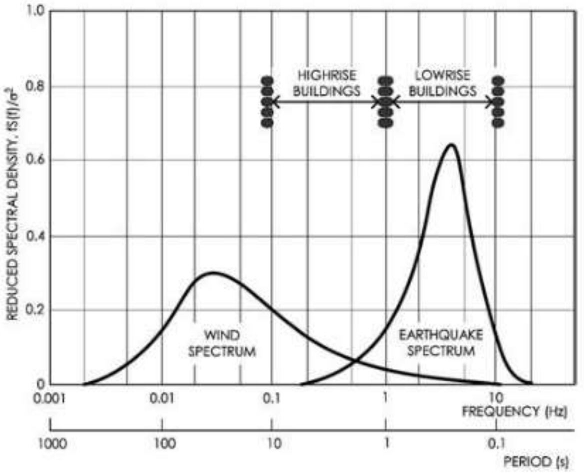


Figure 3: Illustration of wind and earthquake spectrums together with frequency ranges of the structures.

This study is intended for low seismic zones, thus highly focusing on the various possible wind induced effects (as demonstrated in Figure 4) on the design of skybridges.

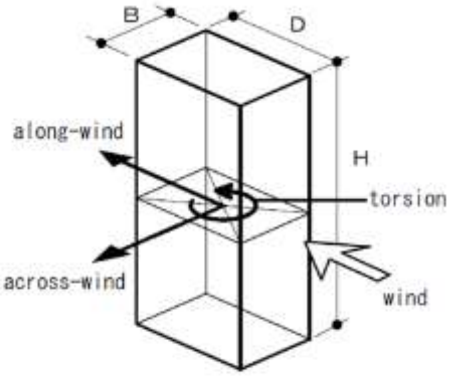


Figure 4: Building vibration response under aerodynamic loads.

4. A Case Study

4.1 Description of the project

A residential high rise twin towers interconnected with a bridge at its roof level has been proposed in Colombo, Sri Lanka. The proposed 10m span skybridge is located at 172 m above the ground level as shown in Figure 5.

Figure 5: Proposed fifty storied twin towers located in Colombo, Sri Lanka and the skybridge connected at the rooftop.

4.2 Structural Design Proposal for Skybridge

For these twin towers, a conventional beam type bridge with steel girders and composite decks was proposed.

All the factors that were discussed in section 4 were considered for the design proposal of the skybridge and the cross-section profile of the proposed bridge is shown in Figure 6. Proposed connection configuration at the four edges of the bridge girders is explained in Figure 9. The connection configuration is carefully chosen considering all the possible movements of the towers under wind and earthquake loadings.

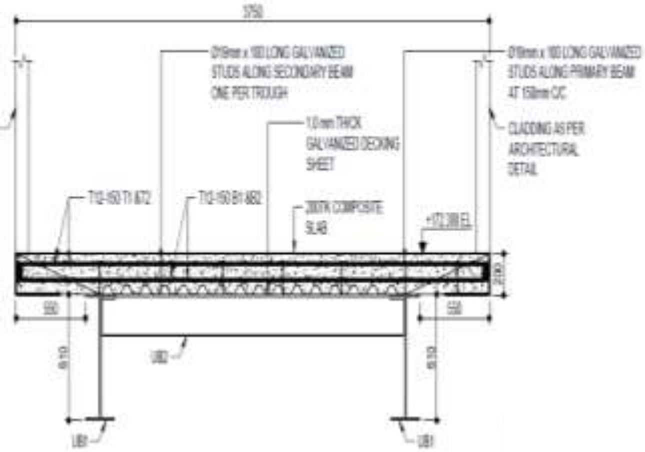


Figure 6: Cross-section of proposed skybridge.

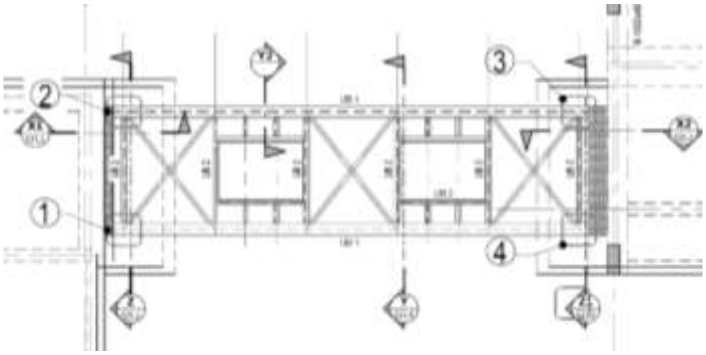


Figure 7: Structural elements of skybridge. (Plan view)

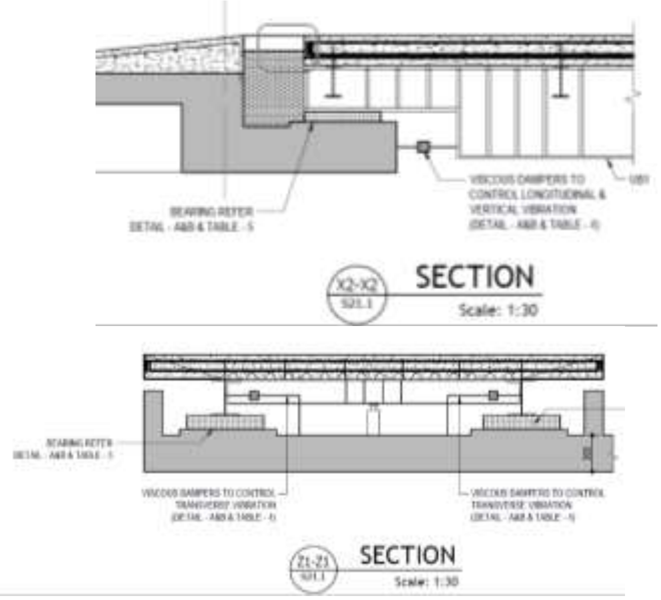


Figure 8: Bridge – Tower connection.

Proposed connection configuration will allow the sliding of the bridge in the longitudinal direction when the towers are moving in longitudinal directions as the bridge is hinged at one position. The movement in transverse direction and twisting of towers are adopted by allowing the rotation of all the connectors in the plane of the bridge along with the longitudinal and transverse movements. Elastomeric bearings, slide bearings and friction pendulum seismic isolation bearings are some of the options investigated for the connection configuration. To facilitate the preferred movements to the bridge, a customized guided slide bearing was chosen as the most suitable connector for the skybridge and the towers. Though friction pendulum bearings provide better performance for similar isolations, light weight of the bridge was a constraint in obtaining adequate friction forces to generate locking forces. Further, consideration of factors such as durability, maintenance requirements, cost involved and low level of seismicity at the project location proofed suitability of slide bearings for this application over elastomeric bearings and friction pendulums.

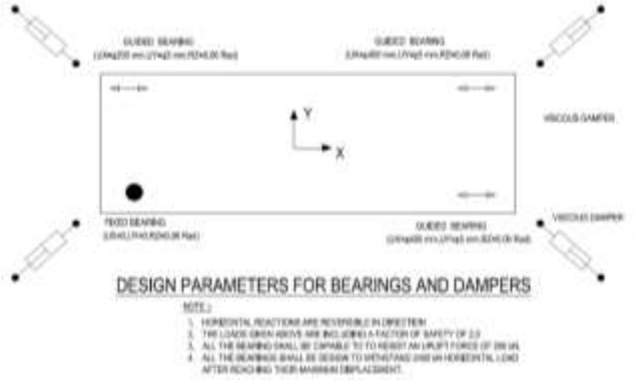


Figure 9: Connector configuration of the skybridge.

Finite element analysis was carried out to investigate the performance of the connection configuration. A roller connected skybrdige was found to be most suitable for this application according to the comparative study carried-out. Excessive relative movement between towers and the roller connected bridge was noticed from the analysis. The dampening solution was proposed in order to mitigate excessive movements. A set of viscous dampers were incorporated together with the connection configuration as shown in Figure 8 and 9 to control the relative movement within the acceptable limit of human comfort.

Figure 10 shows the finite element model used for the analysis of the towers and the bridge. The bearings and the dampers were modelled using the link elements that are available in the commercial finite element software ETABS and SAP 2000. Time history analysis and power spectral analysis were performed on the model illustrated above for wind and earthquake loadings respectively.

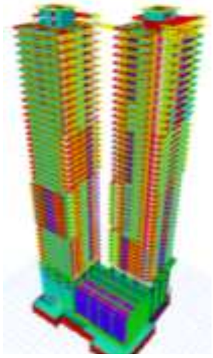
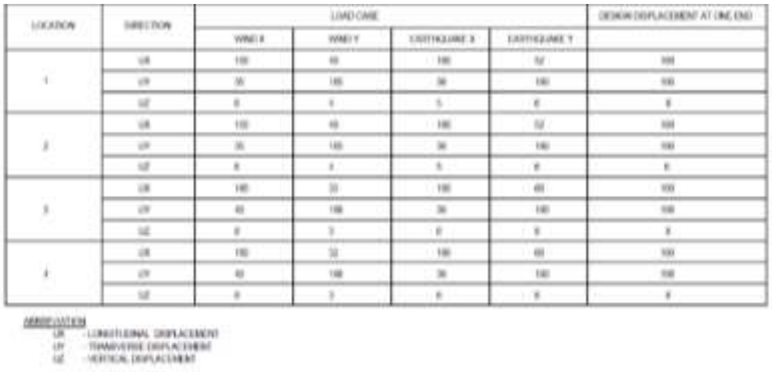


Figure 10: Finite element model used for the analysis

4.3 Analysis results

Table 1 shows the displacements of the towers at the proposed bearing locations for the wind and earthquake loadings together with the gravity loadings. Table 2 summarizes the required cumulative movements of the bearings from the analysis results tabulated in Table 1. Also, the support reactions of the bearings at the maximum displacement under different loading scenarios are presented in Table 4.

Table 1: Displacement of towers at bearing locations in millimetres



LOCATION	DIRECTION	LOAD CASE				DESIGN DISPLACEMENT AT ONE END
		WIND X	WIND Y	EARTHQUAKE X	EARTHQUAKE Y	
1	UX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UZ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	UX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UZ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	UX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UZ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	UX	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UY	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	UZ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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

Table 2: Summary of building displacement for the rollers in millimetres

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

From all the above results, the design parameters for the bearings proposed in Figure 9 are summarized and tabulated in Table 4. And the design parameters of the viscous dampers are tabulated in Table 5.

Table 3: Support reactions for maximum displacements for bearings

Location	Load Case	Force 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

Location	**Load Case**	**Force Direction (kN)**		
		HX	***HY***	***V***
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

Table 4: Design parameters for customized guided slide bearing

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 bearings shall be capable to resist an uplift force of 200 kN
4. All the bearings shall be designed to withstand 2400 kN horizontal load after reaching their maximum displacement

Table 5: Design parameters for the 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

4.4 **Aerodynamics of Skybridge**

Generally, the flow pattern of wind around the building is a complex phenomenon which creating large wind pressures around the building due to the distortions of the wind streamline. The development of wakes and formation of vortices produce large aerodynamic loads on the building surfaces. Various design checks and considerations are adopted in the skybridge in order to minimize the aerodynamic instabilities.

- The natural frequencies of the bridge were kept at least 2.5 times apart from its consecutive closest natural frequency. Thus, the bridge is safe in terms of flutter.

- Spectral density analysis is performed to the bridge to verify the stability against buffeting. Also, the cladding profiles are chosen to avoid the buffeting further as shown in Figure 11.
- Stability against along wind loadings is ensured by the method proposed by Kaimal (1972).
- Stability against vertical vibrations is ensured by the method proposed by Panofsky (1960).

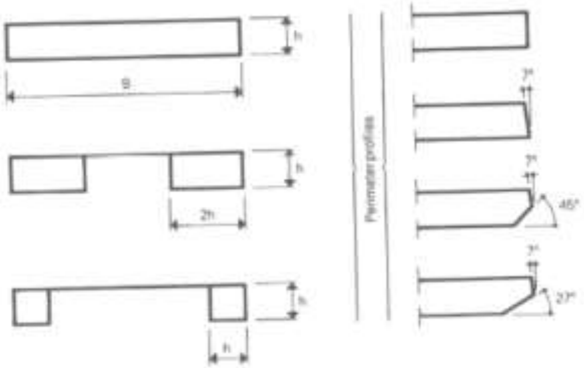


Figure 11: Qualitative recommendations for bridge deck shapes for minimizing vortex shedding.

4.5 Dynamic characteristics of skybridge and evaluation of foot fall vibration

First three free vibration modes and corresponding natural frequencies of skybridge are shown in Figure 12-14.

Figure 12: Higher order flexural vibration mode of skybridge (frequency – 25.5 Hz)

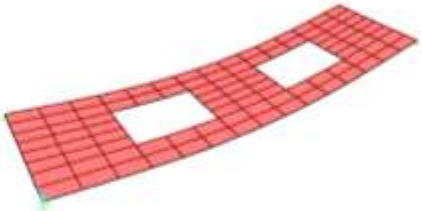


Figure 12: Flexural vibration mode of skybridge (frequency – 6.6 Hz)

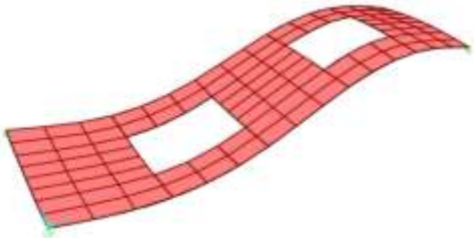


Figure 13: Torsional vibration mode of skybridge (frequency – 19.4 Hz)

Table 6: Geometric details and dynamic characteristics of the towers

Dimensions (b x d x h) /m	**Frequency (Hz)**	**Directional Factors**		
		U_x	U_y	R_z
Tower 1 (27x30x172)	0.180	0.819	0.166	0.016
	0.197	0.178	0.803	0.019
	0.263	0.004	0.033	0.963
Tower 2 (29x26x172)	0.188	0.123	0.867	0.016
	0.205	0.868	0.128	0.004
	0.280	0.019	0.006	0.975

Dynamic characteristics of the towers obtained from model analysis are presented in Table 6. Based on the model properties of the twin towers and skybridge following verifications were made.

- Skybridge is safe from any resonance effects as natural frequency of skybridge is well way from that of the towers

- Ratio between frequencies of Torsional and flexural vibration modes is 2.94 which is larger than 2.5. Thus, sky-bridge is not vulnerable for flutter instability.
- Bridge safe from human discomfort due to footfall vibration, as the first mode frequency of 6.6 Hz is higher than recommended limit of 4 Hz.

5. Conclusion

The design and detailing of the skybridge that connecting fifty storied twin towers, authors have designed is illustrated comprehensively as a case study. The findings and the conclusion of this study are listed below.

- Connection configuration of Skybridges with the tower highly influence the dynamic properties of the towers and consequently it's performance under lateral loading.
- For the bridges with comparatively low stiffness, the roller connections can be used and for the low seismic zones, customized guided slide bearings are most suitable for their connection configuration.
- A finite element analysis is capable to determine the appropriate movements to be accommodated and the forces to be withstood by the bearings.
- 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 to be investigated in roller-connected bridges. A set of properly placed viscous dampers can be used to control the excessive relative movement that 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.
- Selection of suitable profiling for bridge covering is vital to preserving the bridge from the aerodynamic instabilities such as flutter, buffeting and vortex shedding. An optimum bridge profile can be obtained using existing qualitative recommendations or from a computational fluid dynamics simulation.

References

Acharya, A. and Mathur, A. (2016) 'Study of Axial Force in Columns of Coupled Building of different shapes', International Journal of Advance Research in Engineering, Science & Technology, 2444(6), pp. 13–17.

Boggs, D. and Dragovich, J. (2006) 'The Nature of Wind Loads and Dynamic Response', Aci, SP 240, pp. 15–44.

Boggs, D. W., Hosoya, N. and Cochran, L. (2004) 'Sources of Torsional Wind Loading on Tall Buildings: Lessons from the Wind Tunnel', (May), pp. 1–8. doi: 10.1061/40492(2000)85.

Holmes, J., Rofail, A. and Aurelius, L. (2003) 'High frequency base balance methodologies for tall buildings with torsional and coupled resonant modes', 11th International Conference on Wind Engineering, pp. 5–12.

Jean, A. and Mccall, T. (2013) Structural Analysis and Optimization of Skyscrapers Connected with Skybridges and Atria. Brigham Young University - Provo.

Kayali, B. (2014) 'Sky Bridges – Pedestrian Circulation through the Urban Fabric'.

Lee (2012) 'Evaluation of coupling–control effect of a sky-bridge for adjacent tall buildings', The Structural Design of Tall and Special Buildings, 24(March 2010), pp. 421–439.

Richards (2011) Application of Symbolic Computing in Analysis of Modal Properties of Structurally Coupled Twin Tall Buildings. Colorado State University.

Rofail, A. and Holmes, J. (2007) 'High frequency base balance methodology for linked tall buildings', pp. 1–7.

Safarik, D. (2019) 'Skybridges : A History and a View to the Near Future Skybridges : A History and a View to the Near Future'.

Taraldsen, T. (2017) Linking Skyscrapers, A Conceptual Study on Skybridges Effects on the Structural Behaviour of Tall Buildings Subject to Quasi-Static Wind Loads. Norwegian University of Science and Technology.

Tse, K. T. (2013) 'Modal properties of twin buildings with structural coupling at various locations', (2012), pp. 978–981.

Wang (2016) 'Research and Design of a Complex Connected Structure Consisting of Three Super High-rise Towers'.

Wood (2011) 'Rethinking Evacuation : Rethinking Cities Rethinking Evacuation : Rethinking Cities'.

Wood, A. (2003) '"Pavements in the Sky": Use of the Skybridge in Tall Buildings', CTBUH / CIB 2003 Kuala Lumpur Conference, 14(1), pp. 325–332.

Wood, A. and Oldfield, P. (2007) 'Bridging the gap: An analysis of proposed evacuation links at height in the world trade center design competition entries', Architectural Science Review, 50(2), pp. 173–180.

Kaimal, J.C. Spectral characteristics of surface layer turbulence. J. R. Meteorol. Soc. 1972, 98, 563–589.

Panofsky, H.A.; McCormick, R.A. The spectrum of vertical velocity near the surface. J. R. Meteorol. Soc. 1960, 86, 546–564.