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Conjoined Towers for Livable and Sustainable Vertical Urbanism

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Abstract

While tall buildings are an essential building type to accommodate an ever-growing urban population, as buildings become taller and taller, many design challenges arise. As floor spaces are repeated vertically, the occupants' natural horizontal circulation-based social interactions are limited. As buildings become ever taller, safe evacuation to the ground level becomes more challenging in emergencies. With respect to safety as well as serviceability, one of the most fundamental design challenges of exceedingly tall buildings is their structural systems that make the physical existence of tall buildings possible. While many different design solutions can be sought to resolve these issues as well as other design challenges of extremely tall buildings, this paper investigates the potential of conjoined towers to create more livable and sustainable vertical environments. Emphasis is placed on the social and structural capabilities of conjoined towers in providing enhanced social interactions and more efficient ultra-tall structures. The related brief history of conjoined towers is presented. To understand their current status, contemporary design practices of conjoined towers are discussed. Lastly, a new concept of superframed conjoined towers developed for exceedingly tall building complexes is introduced through design studies. Though envisioning future tall buildings is challenging, conjoined towers can be among the strong candidates toward more livable and sustainable vertical urbanism.

Keywords: Tall buildings, Skybridges, Conjoined towers, Structural systems, Sustainable design, Social sustainability, Superframed conjoined towers, Vertical urbanism.

1. Introduction

Tall buildings emerged in the late 19th century typically as office towers. These early multistory office buildings were built with a mixture of interior metal frames and perimeter masonry walls in many cases. As the number of stories were increased to more than about six, passenger elevators became very much necessary, and the employment of the mechanical vertical transportation system accelerated the height increase of tall office towers. The seven-and-a-half-story tall Equitable Building of 1870 in New York is recognized as the first multistory office building of that height with passenger elevators. Five years later, the story height of multistory office buildings increased to about ten stories as were the cases with the Wester Union Building and Tribune Building both in New York. However, these buildings still used perimeter masonry walls for the purpose of both structure and façade, and that was a serious limitation of these early "elevator buildings" to grow taller.

A breakthrough occurred when the metal skeletal frames were also used for the perimeter of multistory buildings. The first tall building of this breed was the Home Insurance Building of 1885 in Chicago with its metal skeletal frame employed for the street facades from the third to tenth story. Since then, tall buildings have continued to become taller and reached the supertall height of over 300 m in the early 1930s and megatall height of over 600 m today. Even the height of over 1 km will be reached soon and the height of one mile (1.6 km) proposed by Frank Lloyd Wright's visionary mile-high tower in the late 1950s will no longer be a vision.

Tall buildings have typically been configured to have many vertically repeated floors. This configuration effectively maximizes the rentable area of the building constructed within limited urban land. However, monotonously repeating many floor spaces vertically does not provide desirable living and working environments for occupants. By replicating floors of limited area, occupants' natural horizontal circulation-based social interactions are limited.

The concept of conjoined towers dates back to the King's Views of New York published by Moses King in the early 20th century. The King's Dream of New York in this publication shows New York skyscrapers connected by "skybridges." Early real-world examples of conjoined towers include the Wrigley Building of 1921 and its north addition of 1924 in Chicago. Originally the two towers were connected only at their lower levels, but the towers were also connected by the skybridge at their 14th floor years later. Since then, conjoined towers have been built sporadically throughout the world mostly with simple skybridges for better circulations between the towers.

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This concept of conjoined towers with connection bridges to provide better circulations between the towers was culminated by the Petronas Towers of 1998 in Kuala Lumpur, the tallest buildings in the world at the time of their completion. As is the case with the Petronas Towers, skybridges in conjoined towers can also be used effectively as alternate routes of evacuation in emergencies. The emergency evacuation has become a very critical design issue of tall buildings especially since the collapse of the World Trade Center twin towers in New York by terrorist attack in 2001.

One of the more recently developed design approaches in conjoined towers is that some of the skybridges are designed to provide substantial programed spaces in addition to circulations. In these cases, the skybridge structures can significantly enhance social interactions between the towers by providing well-positioned large communal spaces within the tower complex as are the cases with the Tencent Seafront Towers of 2017 in Shenzhen, Marina Bay Sands of 2010 in Singapore, The Gate Shams Abu Dhabi of 2013 in Abu Dhabi, and Golden Eagle Tiandi Towers of 2019 in Nanjing.

In terms of structural performance, the skybridges in conjoined towers can also be designed to provide greater lateral stiffness for the whole tower complex. As the structural design of tall buildings is governed by lateral stiffness in general, structural contribution of conjoined towers can be significant. Enhancing structural performances through conjoining towers are highly dependent on multiple factors, such as the number of conjoined towers, their arrangements, and how the towers are connected. Generally, the structural potential of conjoining only two towers is much limited compared to the cases with three or more towers. When three or more towers are conjoined, clustered arrangements have greater structural potential than linear arrangements. And significantly strong and stiff structural connections are required between the towers to maximize the structural potential of conjoined towers.

As today's tall buildings become ever taller to accommodate ever-increasing urban population, developing more efficient structural solutions that can also provide flexible spatial organizations is a very important fundamental design consideration. Furthermore, better resolving concerns about extreme vertical expansions with limited social interaction capacities is crucial for future tall buildings that are becoming ever taller. This paper investigates a viable solution for these important design issues with conjoined towers. While primary emphasis is placed on conjoined towers' potential on enhancing social interactions and structural performance, other design aspects are also considered holistically.

2. Sustainable Vertical Urbanism

Tall buildings began as office towers in many cases. Until the turn of the 21st century, more than 80% of tall buildings over 200 m were still office towers. Today, however, only 43% of tall buildings over 200 m are office towers, 30% are residential (25%) / hotel (4%) / serviced apartment (1%) towers, and 26 % are mixed-use towers. The heights of tall buildings continue to increase, and today's taller buildings tend to be developed more as mixed-use towers. If only supertall buildings over 300 m are considered, 49% of them are mixed-use towers. If the height criterion is further increased to 400 m, 64% are mixed-use towers, while only 26% are offices.[1)]

As a building becomes taller, efforts are often made to produce vertical urban communities of multiple functions instead of developing single function towers. Typical design of mixed-use towers has been vertically stacking multiple functions, and each function group is composed of floors of the same or similar configurations in general. In this case, the resulting design still has a large number of monotonous duplications of floors.

One of the early design concepts developed to overcome

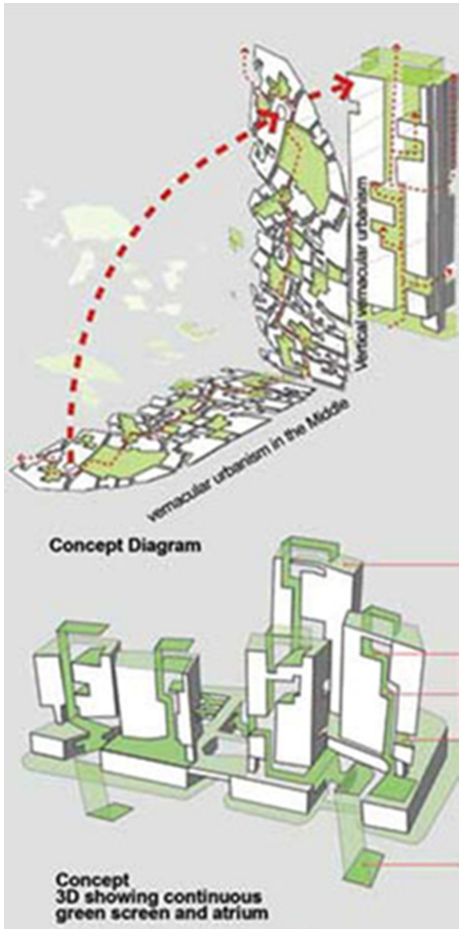


Figure 1. "Vertical vernacular urbanism" by Ken Yeang (Yeang, 2007) © Ken Yeang.

[1)]These statistics are from www.skyscrapercenter.com.

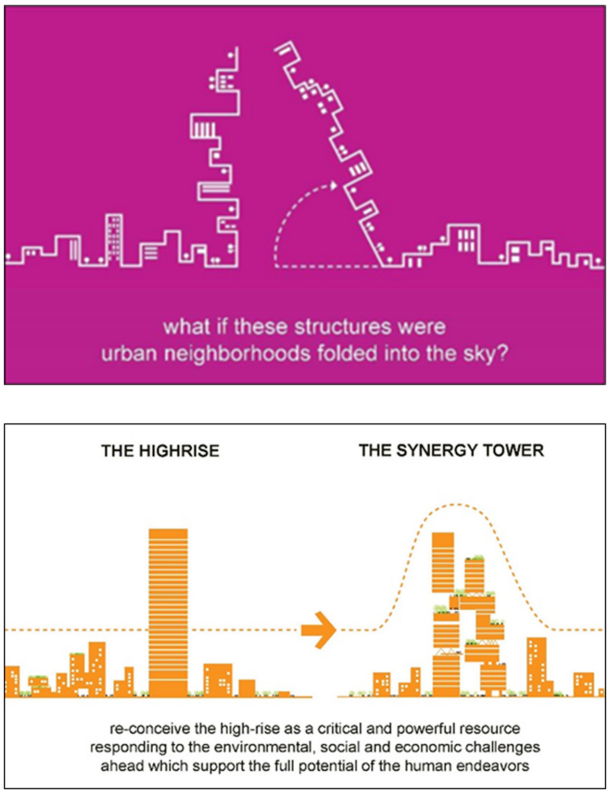


Figure 2. Vertical neighborhood and Synergy Tower concept by NBBJ © NBBJ.

the monotonous vertical repetitions in tall buildings was proposed by Ken Yeang. In his Eco Bay Complex proposal for Abu Dhabi, Yeang developed a "vertical vernacular urbanism" (Figure 1; Yeang, 2007). In this concept, horizontal urban blocks are turned up by 90 degrees to produce a tall building of vibrant urban functions including green spaces embedded along its height.

A similar design concept was also proposed later by NBBJ as "vertical neighborhood" (Figure 2 top; Johnson & Ward, 2018). This concept was further developed into the "Synergy Tower" (Figure 2 bottom; Johnson & Ward, 2018) in which "the high-rise is re-conceived as a critical and powerful resource responding to the environmental, social and economic challenges." NBBJ's example projects employing this concept include the Samsung Learning Center and the Tencent Seafront Towers which are conjoined towers with large programed "skyspaces" between the towers.

OMA also produced design ideas to resolve the issue of monotonously replicating floors in tall buildings. In the "Interlace" in Singapore, a large group of conventional vertical residential towers are reconfigured into horizontally long masses dynamically stacked to produce a uniquely interconnected residential tall building complex (Figure 3). Rooftop areas of the horizontal masses are used as roof gardens in this project. Through this radically different design than any conventional residential tower complex, "an intricate network of living and social spaces" is produced (Scheeren, 2014).

In the KPF's Sky Mile Tower proposal for Tokyo Bay (Figure 4), a mile-high tower complex is composed of residential towers interconnected at multiple levels. This megastructure is in a sense a self-contained city for 55,000 residents (Malott et al., 2015). There are five zones of residential towers vertically distributed and four zones of sky lobbies between them. While the residential zones are composed of three clustered towers that form central open spaces surrounded by them, the sky lobbies interconnect the towers above and below them. The sky lobbies not only perform as vertical transportation hubs but also contain various public facilities, such as shopping malls, restaurants, libraries, and clinics. This overall configuration with vertical residential towers and horizontal sky lobbies integrated with various public functions between them promotes inhabitants' social interactions within the megastructure.

3. Superframed Conjoined Towers

Since the emergence of tall buildings in the late 19th century, many different structural systems have been developed for tall buildings. Among them, some systems have been more suitable for supertall buildings whose

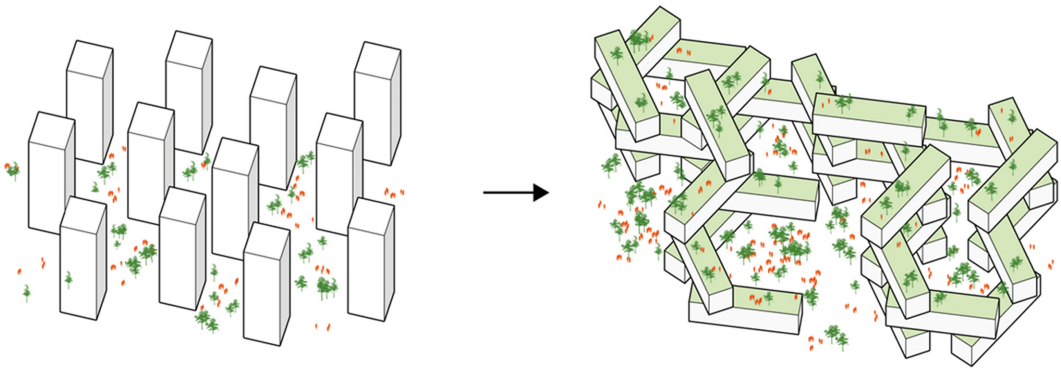


Figure 3. Interlace by OMA © OMA.



Figure 4. Sky Mile Tower by KPF © KPF.

story heights are over about 100 stories in many cases (Figure 5). These systems can broadly be classified into two categories: interior structures and exterior structures (Ali & Moon, 2018). Structural design of tall buildings is generally governed by lateral stiffness against wind loads. Therefore, exterior structures in which major lateral load resisting system components are mostly placed on the building perimeter are more efficient than interior structures where the lateral system components are primarily in the interior of the building. This is because lateral stiffness can be more efficiently increased in exterior structures by using the entire building width as the primary structural depth against wind loads.

The core-outrigger system and more recently developed buttressed core system are two notable interior structures for today's supertall and megatall buildings, while a broader range of tube type systems are available in exterior structures. Despite that exterior structures are structurally more efficient, interior structures - especially the core-outrigger system - are widely used for today's very tall buildings with their enhanced flexibility in façade design because a relatively small amount of structural components is placed on the building perimeter. Nonetheless, exterior structures of various configurations are also prevalently used for contemporary tall buildings of extreme heights.

Structural systems developed for tall buildings have been for stand-alone solo towers. Therefore, the structural depth of exterior structures is still limited to the width of a single building. However, oftentimes, multiple tall buildings are built as a group and they are even interconnected to enhance circulations as well as in some cases to provide substantial programed spaces between the towers. The concept of superframed conjoined towers was developed and proposed by the first author and presented as a structural concept that could reach the tallest height among the exterior structures for exceedingly tall buildings as shown in Figure 5 (Moon, 2018; Ali & Moon, 2018).

In the superframed conjoined towers, multiple towers are interconnected not only architecturally but also structurally. As the braced tube type structure can produce one of the most efficient structural systems for tall buildings (Moon, 2014), it is suggested that the braced tube structure is employed for the individual tall buildings composing the superframed conjoined towers. Further, the braced tube structure is also used for the horizontally bridging structures between the towers. By interconnecting multiple towers with strong and stiff braced tubes, superframed conjoined towers are generated and the towers are interconnected architecturally as well as structurally.

By interconnecting multiple towers at multiple levels and placing various public functions there, social interactions within the tower complex can remarkably be enhanced. As the floor areas at the interconnected levels can be multiple times larger than those of the individual towers, horizontal circulation-based large communal spaces, which are not available in individual tall buildings with limited floor areas, can be produced. This overall configuration can better resolve the critical architectural and social design limitations of independent tower-based tall building complex developments.

Structural benefit toward sustainable engineering could also be significant in the superframed conjoined towers. As tall buildings become ever taller, the required amount of structural materials increases exponentially due to the "premium for height" to resist wind loads in terms of lateral stiffness. Superframed conjoined towers are vertical cantilever towers interconnected by stiff horizontal link structures. As the stiffness and number of links are increased, the tower complex behaves more holistically with the width of the entire complex as the structural depth against wind loads. Then, the premium for height can substantially be reduced in the superframed conjoined towers.

In order to investigate the structural performance of superframed conjoined towers, a 120-story tall braced tube structure and variously configured superframed conjoined towers composed of the braced tubes are com-

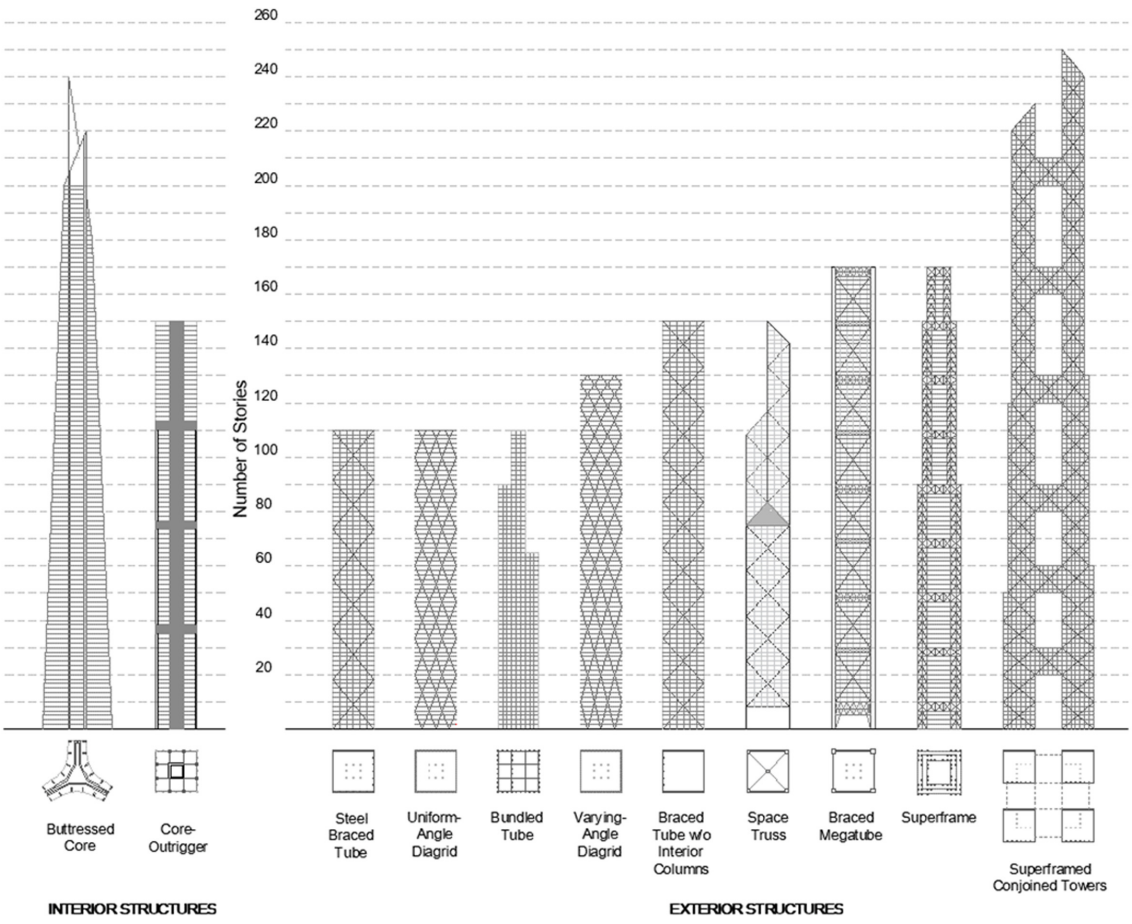


Figure 5. Structural systems suitable for tall buildings over about 100 stories.

paratively studied. The solo braced tube's plan dimensions are 36 m × 36 m with an 18 m × 18 m gravity core at the center, and typical story heights of 3.9 m. The building is assumed to be in Chicago and code-defined wind loads are applied to it. A stiffness-based design methodology developed by the first author (Moon, 2010) is used to design the braced tube to meet the target maximum lateral displacement requirement of a five hundredth of the building height.

For the superframed conjoined towers, four of the 120-story tall braced tube structures are placed with a distance of 36 m between the adjacent braced tubes to form a square shape in plan. The four towers are connected with 10-story tall horizontal braced tubes to study the lateral performance of the superframed conjoined towers in comparison with the solo braced tube. While the initial study is carried out with single braced tube links (Figure 6) of various vertical locations between the adjacent towers, the number of the link structures is increased to investigate the impact of multiple link structures also at various locations.

To present the impact of increasing the number of the link structures, Figure 7 shows comparative wind-induced deformed shapes of four different cases with no, one, two

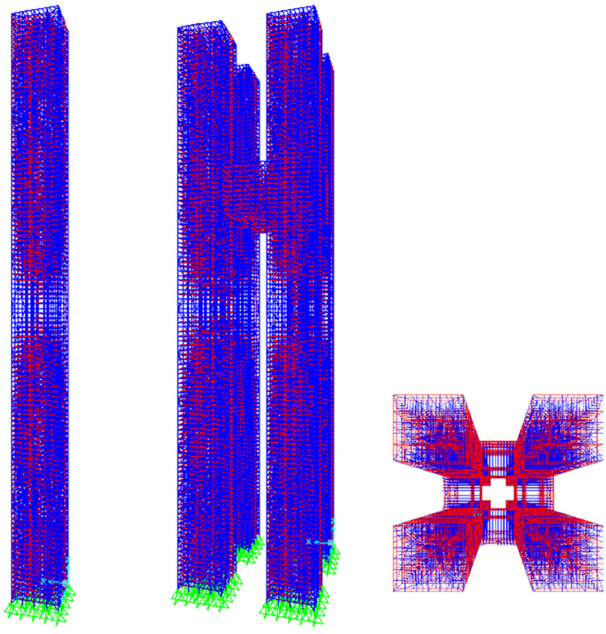


Figure 6. 120-story braced tube and superframed conjoined towers composed of four braced tubes (last image is the superframed conjoined towers seen from above).

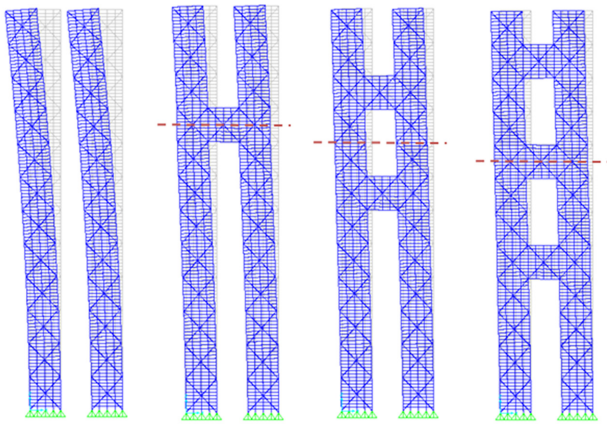


Figure 7. Wind-induced deformed shapes of 120-story superframed conjoined towers with no, one, two, and three link structures at their better locations in terms of lateral stiffness.

and three link structures. Based on many different link locations studied, only the better performing ones in terms of lateral stiffness for each case are presented in the figure. When only one link structure is used between the adjacent braced tubes, the better location of the link is about two-thirds height of the towers. As the number of the link structures is increased, the average height of the links tends to be lowered for better lateral performance. The horizontal dotted lines in the figure show the average height of the link structures.

The impact of placing one link is significant in terms of increasing lateral stiffness. The maximum lateral displacement is reduced by 43% in this study by adding one link between the braced tube towers. Subsequently adding another link structure between the towers further decreases the maximum displacements by 23% and 14% when the number of the link structures becomes one to two and two to three respectively. While Figure 7 presents only selected models that perform better than others structurally in term of lateral stiffness, other design aspects should also be carefully and integratively considered to determine the final configuration of the superframed conjoined towers.

An example configuration of the superframed conjoined towers employed for a megatall complex shown in Figure 8 is composed of four braced tube structures over 1 km tall interconnected by multistory tall horizontal braced tubes at multiple levels. This prototype was developed by Chris Hyun under the guidance of the first author at Yale School of Architecture. Variations are possible with a different number of towers and modified structural configurations. However, if the complex is composed of less than three towers, its structural and spatial capability enhancement is limited in general.



Figure 8. Prototype of superframed conjoined towers.

Despite its characteristics much appropriate for extremely tall buildings, the architecture-integrated structural concept of superframed conjoined towers may not be easily employed for existing dense urban land because very large building sites occupying multiple lots are required for them. However, where appropriate, superframed conjoined towers can be a viable solution to overcome the design challenges of conventional tall building developments composed of independent towers by way of creating more livable and sustainable vertical built environments.

4. Application of Superframed Conjoined Towers for Mile-High Tall Buildings in Chicago

The concept of the superframed conjoined towers is applied to a mile-high tower complex on a site in the Chicago lakefront. The design project guided by the first author was developed by the second author and another graduate student at Yale School of Architecture. One mile long urban blocks containing various vibrant urban functions are considered first and tilted up by 90 degrees to create a mile-high vertical community by occupying only about 10% of the land compared to the corresponding horizontal development (Figure 9 top).

To accomplish the design concept of livable and sustainable vertical urbanism, various urban functions originally considered for the horizontal development are vertically rearranged systematically in terms of spatial organization, form, structure, vertical transportation, etc. It is important to design well-integrated communal spaces throughout the height of the rearranged self-contained-city-like mixed-use tower complex to resolve the critical design issue of many conventional tall buildings with

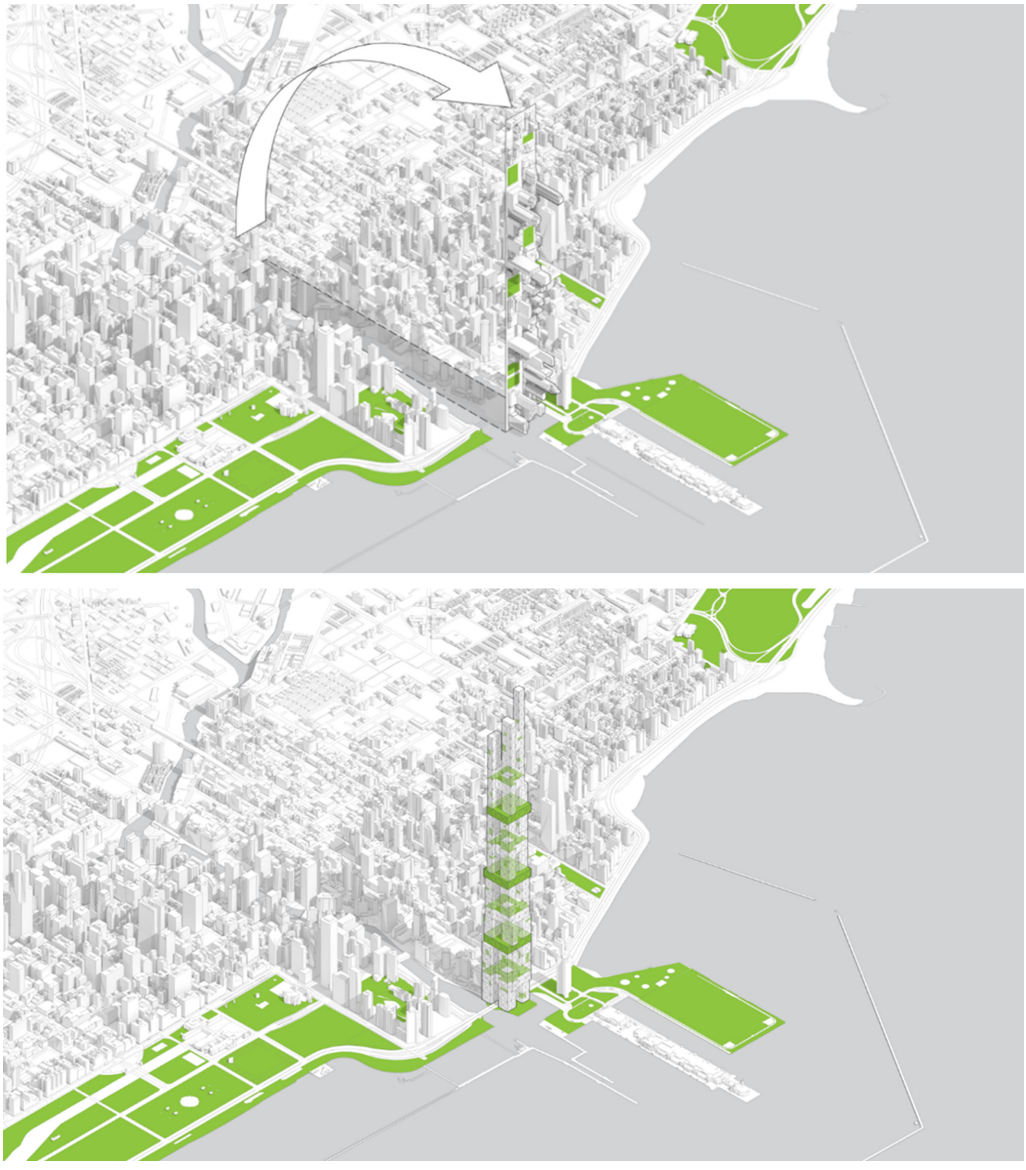


Figure 9. Vertical urbanism concept at Chicago lakefront.



Figure 10. Integratively designed skyspaces throughout the tower complex.

monotonously repeated floors. The towers are primarily composed of offices, residentials and hotels, while the main public spaces, which spatially and structurally interconnect the towers at multiple heights strategically, include convention centers, shopping malls, restaurants, sports facilities, libraries, clinics, etc. In order to serve this mile-high tower complex of an unprecedented extreme height, a new concept of super sky lobbies that are integrated with the main public spaces and lead further to local sky lobbies is introduced. The overall skyspace concept that promotes enhanced social interactions in this mile-high tower complex is not only limited to the main public spaces within the super sky lobby zones but also further integrated into the tower spaces in appropriately reduced scales (Figure 9 bottom & Figure 10).

Link structures between the towers are placed approximately at every 200 m. Beginning from the link structure at the height of about 400 m, every other link structures of multiple stories is devoted to main public functions including super sky lobbies reached by looping rope-less express shuttle elevators. Beginning from the link structure at the height of about 200 m, every other link structures of multiple stories contain local sky lobbies and secondary public spaces. These primary and secondary skyspaces are further branched out in smaller scales into the tower spaces, creating tertiary skyspaces to more intimately engage occupants there.

The structural system is composed of four interconnected braced tubes. Every horizontal link structure is also horizontal braced tubs to maximize the structural depth of



Figure 11. Mile-high superframed conjoined towers at Chica lakefront: daytime view (left) and nighttime view (right).

the tower complex against wind loads through strong and stiff link structures between the towers. The towers taper toward the top by reducing floor areas at the connection link levels. Tapering along with the gap spaces between the towers is important to "confuse" winds to prevent organized alternating vortexes over the height of the towers because lateral vibrations caused by vortex-shedding-induced lock-in conditions are one of the most serious structural design considerations for tall buildings.

The resulting mile-high superframed conjoined towers are gigantic and almost four times taller than the current tallest building in Chicago. While this project can certainly be considered as a city within a city, the design still tries to respond to various contextual issues as well. As the mile-high complex is composed of tapering four towers, the maximum width of which at the ground is about 60 m, and its extreme height is produced with articulated masses, the overall colossal scale of the project is broken into more familiar scales of solo towers commonly experienced in Chicago. As Chicago is also the birthplace of both expressive braced tube system and bundled tube system composed of multiple tubes terminating at different heights, the overall form and structural expression of the superframed mile-high towers are within that context of Chicago as well (Figure 11).

5. Conclusions

This is perhaps not the best time to discuss architecture promoting enhanced social interactions as the pandemic-caused social/physical distancing is recommended throughout the globe. However, mankind will eventually overcome the current difficulty and return soon to the world that could more meaningfully and constructively operate with augmented human interactions. Sustainable design encompassing a broad range of design issues for our future generations as well as promoting social sustainability is zeitgeist for now and for the future.

This paper has presented potentials of conjoined towers as a viable direction for future tall building developments creating more sustainable vertical built environments. By conjoining towers with the concept of the superframe, tall building complexes of extreme heights can be structured with significantly reduced amounts of structural materials compared to the cases with independent towers. As the required amount of structural materials coming from our limited natural resources is exponentially increased as the building height is increased due to the premium for height, superframed conjoined towers' contribution to sustainable engineering can be significant.

One of the most important driving forces of tall building developments has typically been their economic

benefits in dense urban land use. This economy-based tall building developments have produced many towers with maximized rentable spaces by more or less monotonously repeating floors vertically. This design trend has limited social interactions of the occupants within tall buildings. Efforts have been made to overcome this design limitation of tall buildings by introducing variously configured skyspaces that oftentimes dynamically interconnect multiple floor spaces. When multiple towers are conjoined, the potential of creating skyspaces promoting greater social interactions can remarkably be enhanced. This design potential of the conjoined towers along with their structural benefits and many other design possibilities can lead to more livable and sustainable vertical built environments.

Tall buildings take vital places of our built environments in many cities throughout the world. Despite its relatively short history even with recurring skepticisms, this building type has still become essential to accommodate rapid population increase and urbanization. Future of our built environments is dependent upon to a large degree how to design and construct them.

References

Ali, M. M. and Moon, K., 2018. "Advances in Structural Systems for Tall Buildings: Emerging Developments for Contemporary Urban Giants," *Buildings*, 2018, 8(8), 104; doi:10.3390/buildings8080104.

Johnson, T. and Ward, J., 2018. "Designing the High-Rise Building from the Inside/Out," *International Journal of High-Rise Buildings*, Vol. 7-1, pp. 75-84.

Malott, D., Robertson, L., Keisuke, H. and Heidi, W., 2015. "Next Tokyo 2045: A Mile-High Tower Rooted in Intersecting Ecologies," CTBUH Journal: *International Journal on Tall Buildings and Urban Habitat Journal*, *Issue II*, pp. 30-35.

Moon, K., 2018. "Developments of Structural Systems Toward Mile-High Towers," *International Journal of High-Rise Buildings*, Vol. 7-3, pp. 197-214.

Moon, K., 2014. "Comparative Efficiency of Structural Systems for Steel Tall Buildings," *International Journal of Sustainable Building Technology and Urban Development*, Vol. 5-3, pp. 230-237.

Scheeren, O., 2014. "Space Formations," Proceedings of the CTBUH 2014 Shanghai Conference: Future Cities Towards Sustainable Vertical Urbanism, Shanghai, September 16-19.

Yeang, K., 2007. "Eco Skyscrapers," Images Publishing, Mulgrave, Vic.