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Conjoined Tower Structures for Mile-High Tall Buildings

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Abstract

Tall buildings are one of the most viable solutions to deal with the global phenomenon of rapid population increase and urbanization. While tall buildings are an essential building type to accommodate ever-growing urban population, as buildings become very tall they also produce many critical design challenges related to social interactions, emergency egress, structural systems, etc. While many different design solutions can be sought to resolve these challenging issues of tall buildings, this paper investigates potential of conjoined towers in producing more livable and sustainable megatall building complexes with an emphasis on their capability in efficiently providing exceedingly tall building structures.

Keywords: Tall buildings, Structural systems, Skybridges, Conjoined towers, Supertripodded conjoined towers, Superframed conjoined towers

1. Introduction

The world population grows continuously. Today about 55% of the world's population resides in urban areas and the urban population will be further increased to about 70% by 2050 according to the Population Division of the United Nations Department of Economic and Social Affairs. These percentages are obviously world average values. The urban population of North America, the most urbanized region in the world, is already over 80%, while that of Asia is about 50% at present. However, as the urban population in Asia is much more rapidly growing, the gap between the two regions is reducing fast. Tall buildings are one of the most viable solutions to deal with this global phenomenon as evidenced by numerous tall building developments in Asia as well as Middle East over the last couple of decades. Though not as actively as in Asia and Middle East today, tall buildings are still ceaselessly rising in North America, the birth place of tall buildings, and other regions of the world as well.

Developments of tall buildings are certainly not always based on their necessity and/or feasibility. Some tall buildings are developed taller than necessary to express the city's and/or country's growing economic power. Some other tall buildings are built as corporate or individual aspirations. And there are many other non-feasibility-based cases of tall building developments. Nonetheless, tall buildings are still one of the most essential building types for the rapidly-urbanizing future world with dense cities to accommodate ever-growing urban population. They are also becoming taller and taller in order to better redistribute the urban density toward the limitless space in the sky.

Producing higher density is one of the most important aspects of tall buildings. As buildings become taller and consequently occupants are placed farther away from the ground where they can circulate freely without any means of vertical transportation, however, many challenges also arise. As floor plates providing limited areas for each floor are stacked vertically, occupants' natural horizontal circulation-based social interactions are also limited in many tall buildings. As buildings become ever taller, safe evacuation to the ground level in emergencies becomes more challenging. Regarding more about the safety as well as serviceability, one of the most fundamental design challenges for exceedingly tall buildings is also their structural systems that make their physical existence possible. While many different design solutions can be sought to resolve these as well as other challenges of extremely tall buildings, this paper investigates potential of conjoined towers with an emphasis on their capability in efficiently providing megatall structures, the design of which is generally governed by lateral stiffness.

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 a skybridge at their fourteenth floor years later. Since then, conjoined towers have been built sporadically throughout the world mostly with simple connection skybridges for better circulations between the

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towers. This concept of conjoined towers was culminated by the Petronas Twin 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.

One of the more recently developed design approaches in conjoined towers is that some of the connecting skybridge structures are designed to provide substantial programed spaces in addition to conventional circulations between the towers. In these cases, the skybridge structures can significantly enhance social interactions of the occupants by providing well-positioned communal spaces between the towers as are the cases with the Tencent Seafront Towers of 2017 in Shenzhen and Golden Eagle Tiandi Towers currently under construction in Nanjing.

In terms of structural performance, the connecting skybridges in conjoined towers can also be designed to provide greater lateral stiffness for the whole tower complex. As today's tall buildings become ever taller to accommodate ever-increasing urban population, developing more efficient structural solutions that can also provide more flexible spatial organization is another very important fundamental design requirement. The structural potential of conjoined towers depends on multiple factors, such as the number of conjoined towers, their overall arrangement, and where and how to connect them. This paper systematically investigates these important design issues of conjoined towers in terms of their contribution to structural performance in increasing lateral stiffness, while other design aspects are also considered holistically.

2. Conjoined Towers with Two Buildings

When two tall buildings are connected, possibility of meaningfully increasing lateral stiffness of the conjoined towers is largely determined by building forms and connections. By rigidly connecting two buildings with one or more structural bridges, lateral stiffness of the conjoined towers can be increased in the direction of the connecting bridge structures. However, in the perpendicular direction to the connection, the impact of conjoining two towers is minimal. Therefore, as wind can blow in any direction, structural impact of conjoining only two towers is typically limited.

Nonetheless, depending on the conjoined buildings' plan forms, conjoining two tall buildings can still be used strategically to maximize its structural potential. As are the cases with squarish or circular plan buildings for example, when the moment of inertia of the plan forms of the two individual buildings connected are the same or similar in all directions, structural impact of conjoining the towers are limited. However, when plan forms of the two individual buildings are rectangular with significantly different moment of inertia about the two primary axes, by placing the two towers side by side to face broader facade of each tower and structurally connecting them rigidly, lateral stiffness in the originally weaker direction of the individual towers can significantly be increased.



Figure 1. Petronas Twin Towers (Photo in Public Domain).

The 88-story tall Petronas Twin Towers of 1998 in Kuala Lumpur are the world's first conjoined supertall buildings. The primary lateral load resisting system of the towers is the tube-in-tube system composed of the reinforced concrete core and perimeter farmed tube. The two towers are connected by the two-story tall skybridge at levels 41 and 42 using sleeve-like connections, which allow the towers to move independently. Therefore, conjoining the two towers does not increase their lateral stiffness. The plan form of the towers' main masses is roughly circular. Therefore, if the towers are composed of only main masses, even rigidly connecting the towers will not be much beneficial structurally.

However, the towers have smaller bustle masses of circular plan form attached to the main tower masses up to about the height of the connection skybridge. The direc-

tion of the skybridge and that of the bustles attached to the main tower masses are close to perpendicular. Therefore, the towers in fact need greater lateral stiffness in the direction of the skybridge because that is the direction of larger wind load exposure due to the bustle masses. Thus, rigidly connecting the two towers with the skybridge structure could in fact have increased lateral stiffness of the conjoined towers in the direction requiring greater lateral stiffness. Instead of rigidly connecting the two towers, however, Vierendeel outrigger trusses were stretched out from the central core structures of the towers only in the direction of the skybridge and connected to some exterior columns to form core-outrigger structures again only in that direction. Consequently, the lateral stiffness of the towers is increased not by conjoining the towers but by using the unusual Vierendeel outriggers only in the required direction. About 10% of the overturning moment is resisted by the added Vierendeel outrigger system according to the structural engineer.

As could be the cases with rectangular or oval plan form buildings for example, when the moment of inertia of the plan forms of the two towers connected are significantly different in the two primary directions and they are connected in the direction of the smaller moment of inertia of the individual towers, structural impact of rigidly connecting the towers can be significant. In Incheon Tower proposed in 2007, the 151-story tall H-shape plan form building on lower levels splits from level 41, resulting in two separate towers from there. In order to increase the lateral stiffness of the split towers in the direction of the missing web, the towers are connected by four-story tall trusses at mechanical levels placed at every 30 stories. Consequently, the reinforced concrete cores of the split towers and the four story tall connecting trusses form mega-frames to resist lateral loads more efficiently than the otherwise two independent towers in the direction of the missing web.

As discussed previously, when the conjoined two towers' plan forms are squarish or circular individually, the structural impact of rigidly connecting the towers is typically limited as the connection can increase lateral stiffness only in one direction in general while wind can blow in any direction. However, certain configurations can still provide increased lateral stiffness in the two primary directions of the towers. In the proposed Cross # Towers for Seoul by BIG, the two square plan form towers are placed not directly side by side but diagonally with some distance between them. By placing two horizontal masses between the towers in orthogonal direction each other, the two tower structures can be rigidly connected in the two primary directions, producing greater lateral stiffness in both directions, though the stiffness increase with these offset connections is certainly smaller than that with more direct connections.



Figure 2. Inchon Tower, unbuilt (© John Portman & Associates) and its Structural Configuration at the Connection Skybridges (Image Courtesy of Ahmad Abdelrazaq).

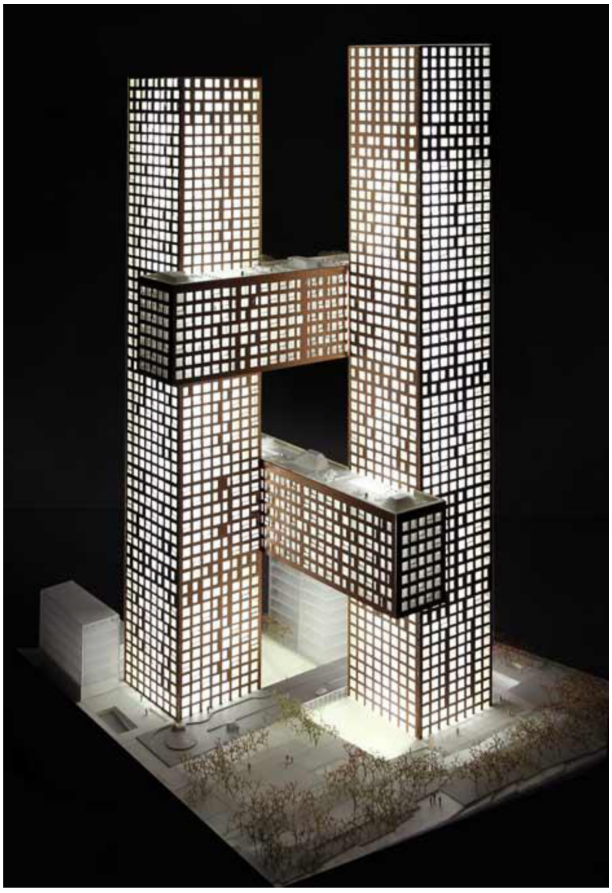


Figure 3. Cross # Towers at Yongsan International Business District (Image Courtesy of BIG - Bjarke Ingels Group).

3. Conjoined Towers with Three Buildings

When three towers are connected, how to arrange them has significant implications for their architectural design and structural performances. When three towers are placed linearly and connected together, their contribution to the increase of lateral stiffness is limited. However, if three towers are clustered to form a triangular configuration and interconnected, the conjoined towers' lateral stiffness can be significantly greater than that of the individual towers.

In the Marina Bay Sands in Singapore, three towers are placed linearly with about 50 m long gaps between them. These towers are connected at the top by the linear SkyPark structure containing rooftop garden, swimming pool and viewing platform. The SkyPark structure is not constructed monolithically with the three main towers. It is composed of five structural segments and four movement joints between them. Therefore, together with the compositional relationship between the three towers and the bridging SkyPark, the SkyPark structure's contribution to the lateral stiffness increase of the towers is negligible, while its gravity loads are transferred vertically to the towers. The lateral stiffness of the towers is provided by the individual tower structures. A very similar design concept is employed in the Raffles City Chongqing, which is under construction at this time, to connect the complex' four towers, T2, T3S, T4S and T5, out of total eight towers.

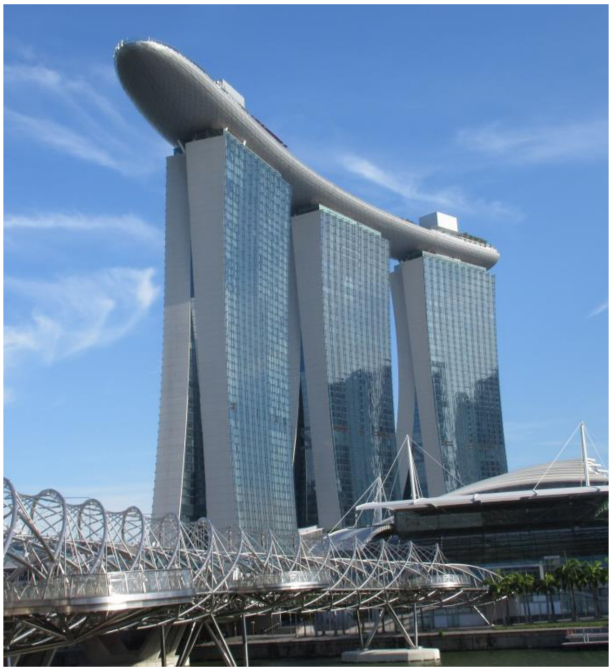


Figure 4. Marina Bay Sands.

Golden Eagle Tiandi Towers, also currently under construction in Nanjing, are the first conjoined towers composed of three supertalls rising 368, 328 and 300 m. Unlike the Marina Bay Sands, the three supertalls are clustered to form a triangular configuration and interconnected structurally with a six-story tall sky lobby at the level of approximately 200 m to enhance the structural potential of the conjoined towers. The individual towers are structured with core-outrigger systems with belt trusses. The connections between the towers are made at the outrigger/belt truss level using five-story tall trusses. These trusses are connected to the belt trusses of the individual buildings, and consequently all three buildings are structurally belted together. By this configuration, the lateral stiffness of the whole conjoined tower structures is much greater than that of the individual towers.

The Sky-Mile Tower project in Tokyo designed by KPF and engineered by LERA also uses a somewhat similar but greatly extended version of the conjoined tower concept composed of three towers to reach the astonishing height of one mile. The conjoined mile-high towers initially rise as three independent towers structured with perimeter columns and diagonals from the ground. At the sky lobby levels placed at every 320 m, the three towers are interconnected by several story tall belt truss structures, while the three towers are also placed with 60 degree rotations



Figure 5. Sky-Mile Tower (Sky-Mile Tower (Image Courtesy of Kohn Pedersen Fox)).



Figure 6. Supertripodded Conjoined Towers.

at every sky lobby level. By these configurations, the lateral stiffness of the entire conjoined tower complex is provided by the structural depth of the whole complex, not by the individual towers.

In the conjoined kilometer-high tower design project by Dana AlMathcoor and Smit Patel at Yale School of Architecture under the guidance of the author, the three megatall towers are tilted toward each other and conjoined at the height of about 500 m above ground. Therefore, the towers perform like three legs of the supertripod structure, significantly increasing lateral stiffness of the conjoined structure compared to the individual towers. Above the conjoining, the three towers are tilted away from each other to stand as individual towers again. The large interior space at the conjoined portion of the towers is designed as various communal spaces shared by the three towers. By conjoining three towers, this project attempts to better resolve the structural and social interaction issues of very tall buildings simultaneously as are also the cases with the previously introduced two projects.

4. Conjoined Towers with Four or More Buildings

Triangles are one of the most structurally powerful forms. Conjoining three towers can result in some unique structural potential in resisting lateral loads compared to conjoining four or more towers. Architecturally, three towers can also be configured as clustered conjoined towers with about 120 degrees between each other, providing better views from each tower than four or more tower configurations. However, as urban grids are usually orthogonal and consequently building lots are rectangular in many cases, opportunities to conjoin three towers forming structurally and architecturally most efficient triangles are limited. Though conjoining four towers might not be as efficient as conjoining three towers, four towers can still be conjoined to produce much greater lateral stiffness than stand-alone towers and at the same time to better fit to more common orthogonal urban grids.

Fazlur Khan, who engineered the braced tube structure of the John Hancock Center in Chicago, stated that “the ultimate possible improvement of the structural efficiency is to go from a multi-column concept to a square tower having only four large corner columns.” Then he employed this concept in a modified way in his superframe, a structural concept proposed for the never-built megatall Chicago World Trade Center. The superframe by Khan employed four large trussed corner columns connected by multi-story deep horizontal trusses at every 20 stories or so.



Figure 7. Superframed Conjoined Towers.

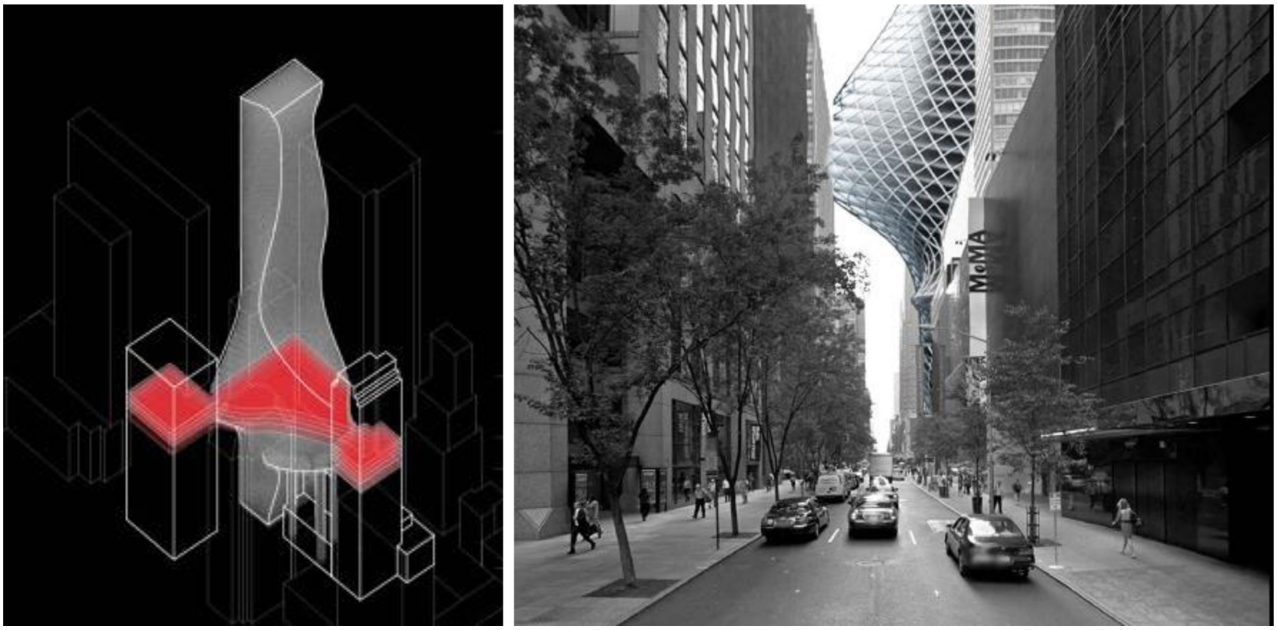


Figure 8. Conjoined Towers by Connecting New and Existing Tall Buildings.

By extending Khan's superframe concept more strategically and in an integrative way with other design aspects, an extremely tall building complex can be produced. In the superframed conjoined towers composed of four towers, four braced-tube towers are placed in the corners of the enormous superframe allowing it to reach a much greater height. The braced-tube towers can be connected by horizontal bands of braced tube structures of multiple story height, which become the connections between the towers housing potentially sky lobbies and other public spaces of truly city-like conjoined mega-towers. At the same time, these are what create the superframed conjoined towers which use the entire width of the tower complex as the structural depth instead of the width of the individual towers. Therefore, the stiffness of the horizontal connection braced tube structures is a very important structural design consideration of these entire tower structures.

Fig. 7 shows a mile-high superframed conjoined tower design project by Chris Hyun at Yale School of Architecture under the guidance of the author for a site in Chicago. In this design project, four exceedingly tall buildings are interconnected with the structural concept of the superframe to create the mile-high conjoined towers.

5. Conjoined Towers with Existing Surrounding Buildings

Conjoined towers can provide viable solutions for various challenging design issues of stand-alone tall buildings, such as social, structural and emergency egress issues as discussed earlier. However, developing new conjoined towers requires very large empty sites usually available only in newly developed cities. In already developed dense cities, clustered multiple available lots are required to develop new conjoined towers. However, these conditions are rare.

When only one lot is available for a new tall building development and the lot is surrounded by multiple existing tall buildings, conjoined towers can be produced by connecting the new tower with the surrounding tall buildings. In order to make these connections without adding additional structures to the existing surrounding building structures, the connections could be achieved by cantilevering skybridge structures of the whole required length only from the newly developed building. In this case, structural potential of resulting conjoined towers in terms of providing greater lateral stiffness will be limited because rigidly connecting the cantilevering skybridge structures with the existing building structures should probably be avoided in most cases. However, this type of design strategy can still produce enhanced social interactions, better emergency egress routes, etc. if designed for these purposes appropriately. Fig. 8 shows a design study of this concept performed by KJ Lee at Yale School of Architecture under the guidance of the author. As urban infill projects are common in already developed dense cities, various potentials of conjoined towers can be explored through this design strategy, which deserves further investigations.

6. Conclusions

In the thousands of years of long architectural history, tall buildings, which emerged in the late 19th century, are still one of the most recent building types. Nonetheless,

despite their history of only about 150 years, tall buildings have been one of the most rapidly evolving building types, and many ambitiously tall proposals have also been made such as Frank Lloyd Wright's mile-high (1.6 km) ILLNOIS in 1950s and Taisei Corporation's 4 km tall X-Seed 4000 for Tokyo in 1990s. However, the world's tallest building at this time is about a half mile tall. When the occupied height is considered, it reached only about one third of a mile. Though a 1 km tall tower is currently under construction, its occupied height will remain around 0.6 km. Though these recent megatall buildings are still astonishing achievements, they are developed as tapered form stand-alone towers. Consequently, while these buildings provide a promising structural prototype for stand-alone megatall buildings, their configurations still have limitations in dealing with multiple challenges of very tall buildings, such as more flexible spatial organizations, better social interactions, and providing multiple routes of emergency egress for enhanced safety.

Potentials of conjoined towers have been discussed in this paper with an emphasis on their structural capabilities for extremely tall buildings. As also discussed in this paper, conjoined towers have great potentials in resolving not only structural but also aforementioned other tall building related critical design issues simultaneously. Certainly, conjoined towers also have their inherent limitations such as requiring very large sites or multiple lots. Where appropriate, however, these towers can still be a viable solution for the problem of dense urban environments with ever-increasing population by providing more livable and sustainable vertical cities with tall buildings integratively interconnected in various aspects.

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