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Superframed Conjoined Towers for Sustainable Megatall Buildings

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Abstract

Tall buildings have generally been developed as solo towers. With the increase of the heights of tall buildings from about 10-story buildings to supertall and megatall buildings, their structural systems have evolved from interior structures to exterior structures and combined/mixed systems. This paper reviews structural systems developed for solo supertall and megatall buildings and discusses the challenges they face in terms of structural performance and architectural design as the building heights are ever increased. As a viable and more sustainable design alternative to extremely tall solo towers, superframed conjoined towers are presented. Their structural performances are investigated in comparison with solo tower structures. Further, architectural potentials of superframed conjoined towers are explored through design studies.

Keywords: Tall buildings, Megatall buildings, Structural systems, Conjoined towers, Superframed conjoined towers, Sustainable design

1. Introduction

Tall buildings emerged in the late 19th century in the U.S. as office towers of about 10 stories. Since then, the height of tall buildings increased rapidly. Around the turn of the century, the height of tall buildings reached 30 stories with the Park Row Building in New York, and in 1931 it surpassed 100 stories with the Empire State Building also in New York. This was the culmination of the height race of early tall buildings as no more tall buildings over 100 stories were built until the late 1960s and the record height was not broken until the early 1970s.

In 1956, when the 381 m tall Empire State Building with 102 stories was still the tallest building in the world, Frank Lloyd Wright proposed the mile-high ILLINOIS with 528 stories. At its height of about 1.6 km, the proposed ILLINOIS is more than four times taller than the Empire State Building. With over 18 million square feet (about 1.7 million square meter) of gross floor area, the ILLINOIS was designed for the grand total occupancy of about 130,000 people.

At present, the 828 m tall Burj Khalifa of 2010 in Dubai is the tallest building in the world. Its height is about a half of the mile-high tower. Further, the height of 1 km will be reached by the Jeddah Tower in Jeddah though its construction that started in 2013 is currently on hold. It is noted that the occupiable heights of the former and the latter are 585 m and 600 m+ respectively. There are some substantial gaps between the architectural and occupiable heights. Nonetheless, the height race has been continued and mile high towers will not be just a vision especially in terms of architectural height in the foreseeable future.

Many tall buildings, including supertalls, megatalls, and tallest buildings in the world of different time periods, have been developed as solo towers. The visionary ILLINOIS was also proposed as a solo tower. While solo towers have been the mainstream of tall building developments, they have some inherent design challenges, especially as tall buildings become ever taller.

For a very tall building, its structural design is generally governed by lateral stiffness. As a building becomes taller, the amount of structural materials needed to meet this design requirement is increased exponentially, while that of other building materials is increased more or less proportionally. Tall buildings are gigantic and constructed with enormous amounts of materials. Therefore, it is very important to employ efficient structural systems for very tall buildings to save structural materials coming from our limited natural resources and produce more sustainable built environments. In order to obtain the maximum lateral stiffness more efficiently with a solo tower, the tower's entire width is used as its structural depth against lateral loads in general. Then, as a building becomes taller and taller, it is better to increase the width of the building to create a more efficient structure. However, greater building widths may result in deep and uncomfortable interior spaces.

Another issue of solo tall buildings of ever-increasing heights is about social sustainability in terms of interactions of the people within the building. As tall buildings become ever taller, more and more floors are stacked vertically. Consequently, dynamic interactions between occupants and users by more natural and comfortable horizontal circulations are limited in solo towers.

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This paper reviews structural systems for exceedingly tall buildings. As a viable and more sustainable design alternative to better resolve the inherent design challenges of solo tall buildings, conjoined towers are studied. As an efficient structural solution for conjoined tall buildings, superframed conjoined towers are introduced and their structural performances are investigated. Further, superframed conjoined towers' architectural potentials are explored through design studies carried out by graduate students guided by the author at the Yale School of Architecture.

2. Structural Systems for Supertall and Megatall Buildings

There have been six tall building projects with the title of the tallest building in the world since the Empire State Building of 1931. Table 1 shows the structural systems of these tallest buildings. The Empire State Building employed a typical interior structure at that time, i.e., braced moment resisting frame around the building core, as its primary lateral load resisting system. About three decades later, the One World Trade Center and Sears Tower employed newly developed exterior structures at that time to maximize their structural depths. The former and the latter used framed tube and bundled tube respectively. This transition reflected the evolution of structural systems for tall buildings toward enhanced efficiency with increased structural depths by engaging building perimeter structurally against lateral loads.

Tallest buildings later on, however, do not solely rely on exterior structures for greater efficiency only. The Petronas Towers employ both interior core and exterior framed tube as their lateral load resisting system, while the Taipei 101 and Burj Khalifa use interior structures that still try to engage the entire building width. The core-outrigger and buttressed core systems use the interior cores as their major lateral load resisting systems. However, perimeter megacolumns are connected to the core through outriggers in the former and buttressing shear walls are stretched out toward the building's perimeter from the central core in the latter. These design approaches provide greater flexibility in façade design than tube type exterior structures, while structural efficiency is not too much sacrificed.

In order to better understand recent structural design trends for exceedingly tall buildings, Table 2 summarizes structural systems for megatall and 500 m+ tall buildings. The Taipei 101 was the first tall building that broke the height of 500 m. Today, there are total 10 tall buildings exceeding 500 m in the world. Among them, three are over 600 m and these are categorized as megatall buildings. In addition, several tall buildings in the height range of 500 m+ under construction, on hold, or proposed are included in Table 2.

Pure exterior structures are rarely used in today's tall buildings. Core structures are almost always engaged in the primary lateral load resisting systems in recent tall buildings. They are usually designed as concrete shear walls to act as a second line of defense. This is almost standardized practice for tall building structures throughout the world after the tragic September 11 attacks on the World Trade Center Twin Towers, one of which was once the tallest building in the world.

Core structures are used to form core-outrigger structures or buttressed core structures as discussed earlier. In addition to these uses, core structures are used in combination with exterior tube type structures. Further, core-outrigger structures are mixed with exterior megatube type structures by sharing perimeter megacolumns. These combined or mixed systems are developed to meet various project specific requirements and maximize structural efficiency.

While conjoining tall buildings has greater design potentials structurally and architecturally than developing solo tall buildings as will be discussed in detail in this paper, a very limited number of exceedingly tall buildings are conjoined towers. In Table 2, there are only two conjoined tower projects, Makkah Royal Clock Tower of 2012 within the Abraj Al-Bait Endowment Complex and Thai Boon Roong Twin Towers with very limited information. Therefore, the range for the review of extremely tall conjoined towers is expanded to include all supertall buildings in this category. Currently, there are about 180 supertall buildings over 300 m in the world. Among them, only nine are parts of conjoined towers including one megatall building. Table 3 shows these towers along with conjoined tower complex composing buildings that are either also supertalls or 200 m+ buildings. In terms of number of projects, these represent only five projects. Among these, only one project uses structural potential of

Table 1. Structural systems for tallest buildings in the world since 1931

Building	City	Tallest Period	Height (m)	Story	Structural System
Empire State Building	New York	1931-1972	381	102	Braced Moment Resisting Frame
One World Trade Center, Demolished	New York	1972-1974	417	110	Framed Tube
Sears Tower (now Willis Tower)	Chicago	1974-1998	442	108	Bundled Tube
Petronas Towers	Kuala Lumpur	1998-2004	452	88	Tube-in-Tube
Taipei 101	Taipei	2004-2010	508	101	Core-Outrigger
Burj Khalifa	Dubai	2010-present	828	163	Buttressed Core

conjoined towers by structurally coupling the towers.

Generally, the structural potential of conjoining only two towers is limited because the connections can typically increase the conjoined towers' lateral stiffness only in one direction when the two towers are structurally coupled. Conjoined towers composed of three or more towers have much greater potential. When three or more towers are conjoined, clustered arrangements can provide superior lateral stiffness in all directions. Among the projects listed in Table 3, the Golden Eagle Tiandi Towers are composed of three clustered and structurally coupled tall buildings. Consequently, this project takes advantage of this configuration structurally in terms of increasing the lateral stiffness of the complex. As the three towers are interconnected rigidly, the structural depth against lateral loads is increased to the width of the entire complex.

Table 2. Structural systems for megatall and 500 m+ buildings

Building	City	Year	Ht. (m)	Story	Structural System
Jeddah Tower	Jeddah	Under Constr.	1000+	167	Buttressed Core + Fin Walls
Burj Khalifa	Dubai	2010	828	163	Buttressed Core + Fin Walls (w/ Outrigger)
Merdeka PNB118	Kuala Lumpur	Topped Out	644	118	Core-Outrigger + Braced Megatube
Shenzhen Tower	Shenzhen	Proposed	642	128	Braced Megatube + Core
Signature Tower	Jakarta	Proposed	638	113	Core-Outrigger + Megaframe
Shanghai Tower	Shanghai	2015	632	128	Core-Outrigger
Makkah Royal Clock Tower	Mecca	2012	601	120	Core + Shear Walls
Ping An Finance Center	Shenzhen	2016	599	115	Core-Outrigger + Braced Megatube
Goldin Finance 117	Tianjin	On Hold	597	128	Braced Megatube + Core
Hyundai Global Business Center	Seoul	Proposed	569	105	Braced Megatube + Core
Thai Boon Roong Twin Towers	Phnom Penh	Proposed	562	133	N/A
Lotte World Tower	Seoul	2017	555	123	Core-Outrigger
One World Trade Center	New York	2014	541	94	Core + Perimeter Moment Resisting Frame
Guangzhou CTF Finance Centre	Guangzhou	2016	530	111	Core-Outrigger
Tianjin CTF Finance Centre	Tianjin	2019	530	97	Core + Perimeter Sloped Column Frame
CITIC Tower	Beijing	2018	528	108	Braced Megatube + Core
Guizhou Culture Plaza Tower	Guiyang	Proposed	521	109	Superframe + Core
Evergrande Hefei Center T1	Hefei	On Hold	518	112	Core-Outrigger + Megaframe
Taipei 101	Taipei	2004	508	101	Core-Outrigger

Table 3. Conjoined tower projects including 300 m+ supertall buildings within the complex

Complex	Building	City	Year	Ht. (m)	Story	Structurally Coupled/Uncoupled
Abraj Al-Bait Endowment	Makkah Royal Clock Tower	Mecca	2012	601	120	Uncoupled
	Abraj Al Bait ZamZam Tower	Mecca	2012	279	58	
	Abraj Al Bait Hajar Tower	Mecca	2012	276	54	
Petronas Towers	Petronas Twin Tower 1	Kuala Lumpur	1998	452	88	Uncoupled
	Petronas Twin Tower 2	Kuala Lumpur	1998	452	88	
Golden Eagle Square Plaza	Golden Eagle Tiandi Tower A	Nanjing	2019	368	77	Coupled: three clustered towers are coupled with multistory trusses.
	Golden Eagle Tiandi Tower B	Nanjing	2019	328	60	
	Golden Eagle Tiandi Tower C	Nanjing	2019	300	58	
Raffles City Chongqing	Raffles City Chongqing T3N	Chongqing	2019	355	79	Uncoupled
	Raffles City Chongqing T3S	Chongqing	2019	265	46	
	Raffles City Chongqing T4N	Chongqing	2019	355	79	Uncoupled
	Raffles City Chongqing T4S	Chongqing	2019	265	50	
East Pacific Center	East Pacific Center Tower A	Shenzhen	2013	306	85	Uncoupled
	East Pacific Center Tower B	Shenzhen	2013	262	72	

Further, the bridging structure of the towers provides large communal spaces shared by all three towers and resolves a critical architectural design issue of solo towers in terms of social sustainability by promoting interactions of the occupants and users of the complex.

3. Structural Performance of Superframed Conjoined Towers

Individual buildings of the Golden Eagle Tiandi Towers are structured with core-outrigger systems and multistory trusses are used to interconnect clustered towers around the belt truss levels of the outrigger systems so that all tower structures behave holistically. In this section, structurally interconnected towers of braced tubes are studied, and they are called superframed conjoined towers. Although core-outrigger structures are an efficient system to carry lateral loads for tall buildings, they are typically not as efficient as exterior structures, such as braced tubes, one of the most efficient tube type structures.

Figure 1 shows the required amount of structural steel for core-outrigger structures and braced tubes of various story heights ranging from 40 to 100 stories. The building's plan dimensions are 36 m × 36 m with an 18 m × 18 m core at the center. The cores are designed with braced frames to participate in carrying lateral loads in the outrigger structures, while they are designed to carry only gravity loads in the braced tubes. Typical story heights are 3.9 m. The braced tube system for the building is composed of perimeter columns placed at every 9 m and large X diagonal bracings with their module height of 10 stories. In the outrigger system, outriggers are placed at every 20 stories except at the top, and two perimeter columns on each side is designed as megacolumns and connected to the outriggers. The buildings are assumed to be in Chicago and code-defined wind loads are applied.

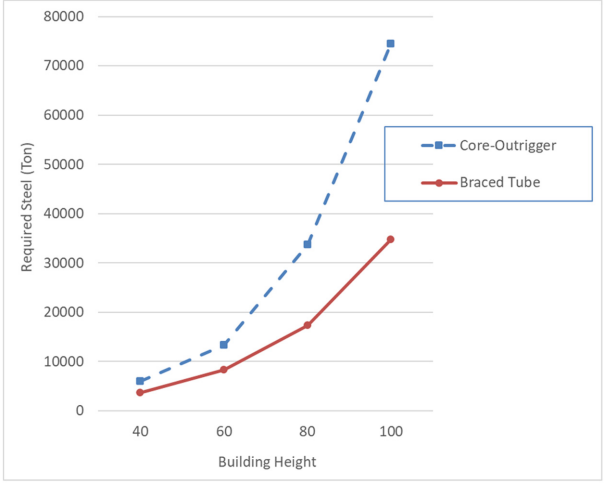


Figure 1. Required structural steel for the 40-, 60-, 80- and 100-storey outrigger and braced tube structures.

Stiffness-based design methodologies are used to design the structures optimally to meet the target maximum lateral displacement requirement of a five hundredth of the building height. Structural steel is used for all structural elements for the purpose of clear comparison. As can be seen in the figure, braced tubes use less amounts of steel than outrigger structures, and this tendency is accelerated as the building height is increased.

3.1. Superframed Conjoined Towers with Single Link Structures

In order to study the performance of superframed conjoined towers employed for exceedingly tall buildings, now a 120-story braced tube structure is designed first. The building's important dimensions are the same as described earlier for the comparative study. The building is assumed again to be in Chicago and code-defined wind loads are applied. A stiffness-based design methodology developed by Moon (2010) is used to design the braced tube structures optimally to meet the target maximum lateral displacement requirement of a five hundredth of the building height. According to the method, the optimal bending to shear displacement ratio of the studied 120-story braced tube structure is about 4.5 for the most efficient design with the least amount of structural material to meet the target displacement requirement.

When multiple towers are clustered, they are often connected by single link structures between the adjacent towers. To investigate the structural performance of superframed conjoined towers with one link structures between the adjacent towers, two braced tube structures of 120 stories are connected by a 10-story tall horizontal braced

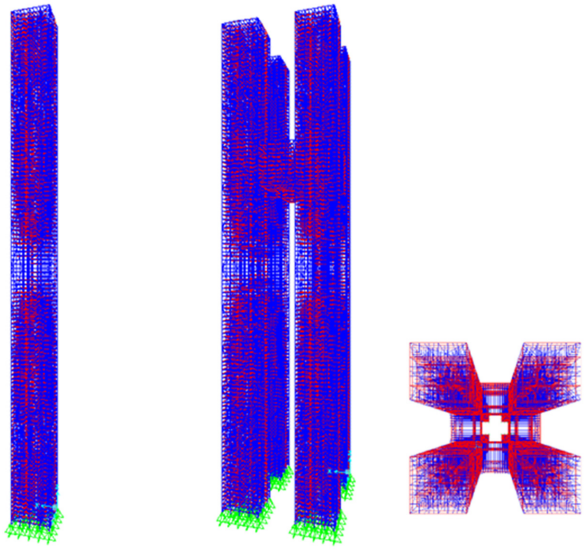


Figure 2. 120-story braced tube and superframed conjoined towers composed of the four braced tubes. (the last image is seen from above showing all link structures between the towers)

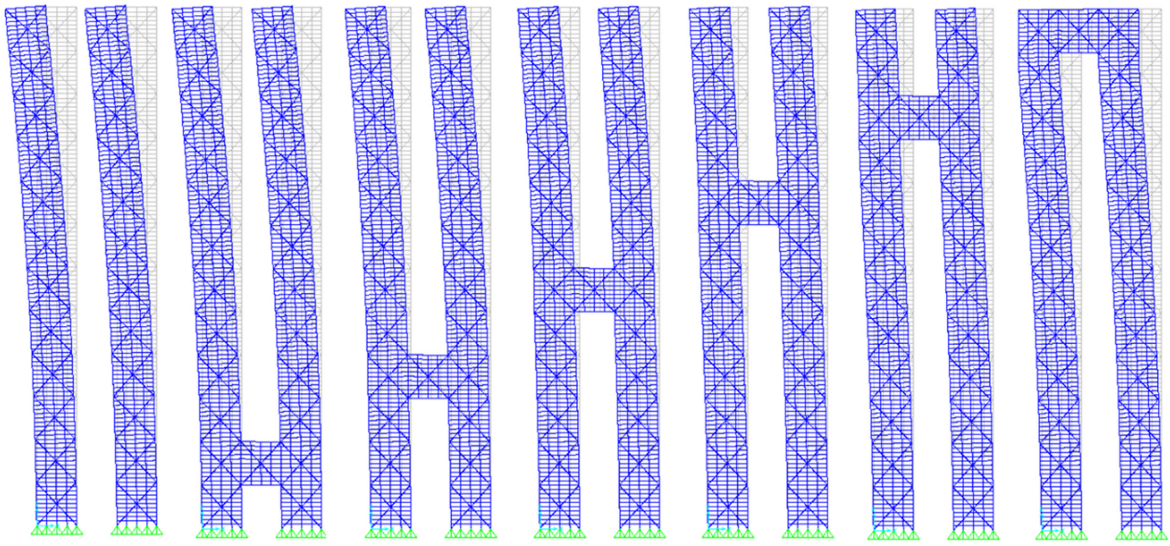


Figure 3. Wind-induced deformed shapes of 120-story superframed conjoined towers with a single link structure at various heights between the adjacent towers. (deformation is exaggerated by a scale factor of 30 for clarity)

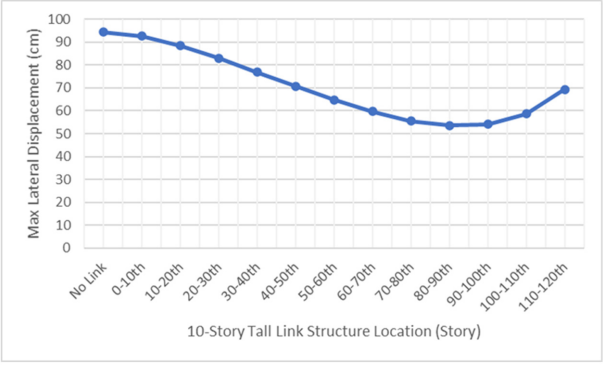


Figure 4. Maximum lateral displacements at the top of 120-story superframed conjoined towers with no and single link structure at 12 different locations.

tube structure, and the code-defined lateral wind load is applied only in the direction of the connection, i.e., the strong direction. Therefore, this is in a sense a partial model's static response study of the superframed conjoined towers composed of four braced tube structures shown in Figure 2. The link structure is placed at 12 different heights by relocating it continuously at an interval of 10 stories. The shear stiffness required for the mid-height of the tower from level 60 to 70 is used to design the bracings of the link structure. For the purpose of the comparative study, the same link structure is used regardless of its vertical location between the towers. Therefore, every conjoined tower structure comparatively studied is designed with the same amount of structural steel.

Including the case with no link structure, total 13 cases are studied. Figure 3 shows seven selected cases among them, while the maximum lateral displacements at the top of all 13 cases are plotted in Figure 4. As can be observed from the figures, the maximum lateral displacement of

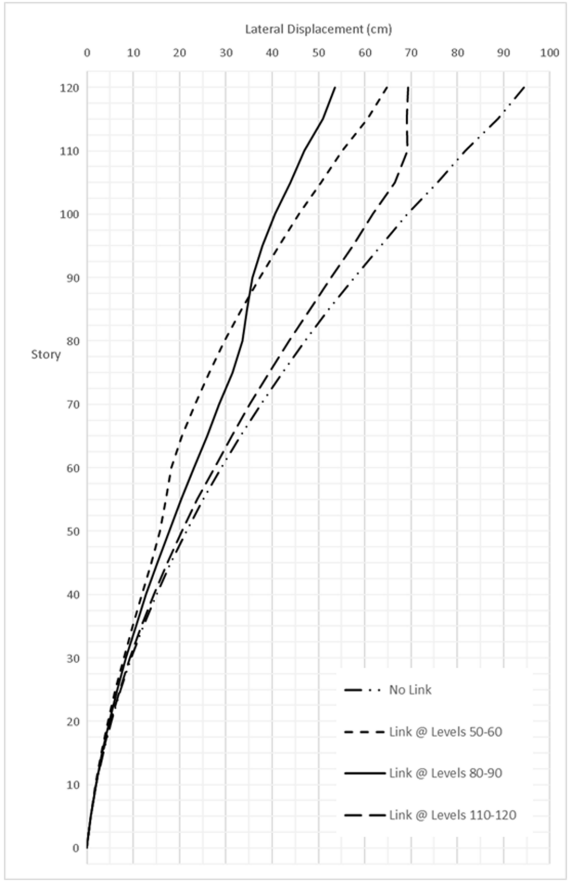


Figure 5. Comparative deformed shapes of the superframed conjoined towers with no link and single link at mid-height, two-thirds height and at the top.

the superframed conjoined towers is gradually reduced as the link structure is moved from the bottom to about two-thirds height of the tower. As the link structure is further

moved up from the two-thirds height to the top, the maximum lateral displacement is gradually increased again.

To observe more clearly the impact of the location of the single link structure on the deformed shapes and maximum lateral displacements of the superframed conjoined towers, Figure 5 shows four selected cases together. The compared four cases are the superframed conjoined towers with no link and single link structure at mid-height, two-thirds height and at the top. When there is no link, the braced tube structure behaves like a vertically cantilevered bending beam. When a ten-story tall link structure that rigidly connects the adjacent towers is introduced, curvature reversals occur around the link. Then, the proportion of the tower's partial heights below and above the link structure is important in terms of its optimal location to minimize the maximum lateral displacement at the top of the tower. As can be seen from the figure, the best proportioning occurs when the location of the link is about two-thirds height.

3.2. Superframed Conjoined Towers of Braced Tubes vs. Braced Megatubes

A similar study is carried out with superframed conjoined towers composed of braced megatubes. As presented in Table 2, braced megatubes are used frequently in today's tall buildings of extreme heights. The main difference between the braced tubes and braced megatubes is that in the braced tubes, regularly spaced multiple perimeter columns are placed on every side of the building, while in the braced megatubes, main perimeter columns are placed only at the corners as megacolumns (Figure 6). Therefore, braced megatubes are more efficient than braced tubes in providing bending rigidity against lateral loads. Consequently, for independent towers, braced megatubes can be designed and constructed with less amounts of structural materials.

The stiffness-based design methodology used for the braced tubes is also applied to the braced megatubes of the same heights and aspect ratios. The optimal bending to shear displacement ratio of the studied 120-story braced megatubes structure is about 4 for the most efficient design with the least amount of structural material to meet the target displacement requirement. It is noted that the ratio for the braced tube was 4.5 as presented earlier. This difference occurs because the bending to shear rigidity ratio is larger in the optimally designed braced megatubes than in the braced tubes of the same heights and aspect ratios. Therefore, the bending to shear displacement ratio is smaller in the braced megatubes.

Four corner megacolumns are used to form the braced megatubes. Between the corner megacolumns, in fact, much smaller gravity columns are placed at every 9 m in the actually studied braced megatubes as can be seen in Figure 7 since the 36 m spacing between the megacolumns would be too wide to span economically otherwise. At every 20 stories, transfer trusses are placed between the corner megacolumns so that the gravity loads from the gravity columns can be transferred to the megacolumns. Elevation and partial three-dimensional views of the studied 120-story braced tube structures are also shown comparatively in Figure 7. Core structures that are designed to carry only gravity loads exist but are omitted from the view for clarity. For the 120-story steel tall buildings studied in this paper, in order to meet the same maximum lateral displacement target of a five hundredth of the building height, the braced megatube uses about 26% less structural steel than the braced tube.

When a link structure is added between the braced megatubes to form superframed conjoined towers composed of braced megatubes, its impact on increasing lateral stiffness is similar to the cases with the superframed conjoined towers with braced tubes. Figure 8 shows the comparative maximum lateral displacements at the top. It is noted that the solo braced megatube was designed to have slightly less lateral displacement than the solo braced tube due to the tolerances of the stiffness-based design methodology. In both cases, as the link structure is moved up from the bottom to about two-thirds height, the lateral stiffness is continuously increased. When the link structure is placed at about two-thirds height, the lateral stiffness of

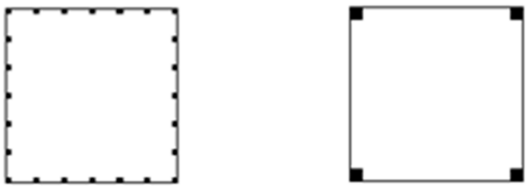


Figure 6. Simplified typical perimeter column arrangements of braced tubes (L) vs. braced megatubes (R) in plans. (gravity columns are usually placed between the corner mega-columns in real-world braced megatube projects but are omitted in this figure for clearer conceptual comparison)

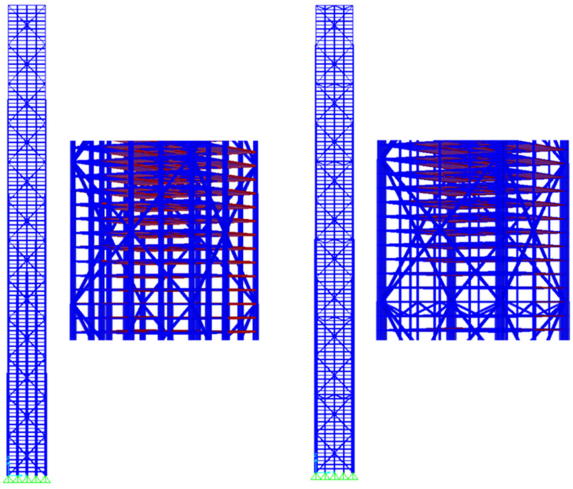


Figure 7. Elevation and partial three-dimensional views of the braced tube (L) and braced megatube (R) structures. (core structures exist but omitted from the view for clarity)

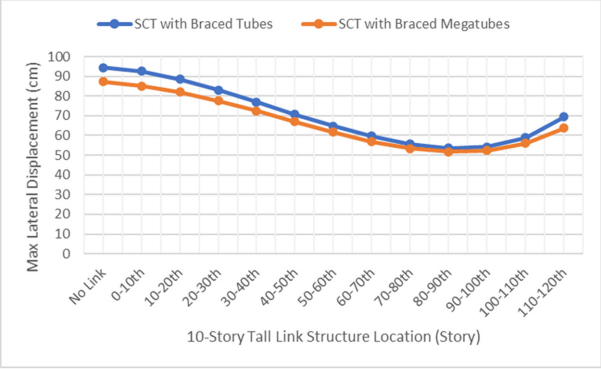


Figure 8. Comparative maximum lateral displacements of 120-story superframed conjoined towers of braced tubes vs. braced megatubes with no and single link structure at 12 different locations.

the conjoined towers is maximized. In fact, when only the impact of structurally coupling the towers is considered, the superframed conjoined towers composed of braced megatubes are somewhat less sensitive in terms of stiffness increase. This is because not all corner megacolumns of the individual braced megatubes are at the corners of the conjoined tower complex when the towers are linked. In fact, 50% of the corner megacolumns in the individual towers are placed close to the neutral axes of the conjoined tower complex.

3.3. Superframed Conjoined Towers with Multiple Link Structures

Studies on the structural performance of superframed conjoined towers are expanded with those with two, three and four link structures between the adjacent towers. Adding more skybridges further increases lateral stiffness of the superframed conjoined towers. Figure 9 presents wind-induced deformed shapes of the two solo braced tube towers and selected best cases with one, two, three and four link structures among many studied alternatives with link structures at various different locations. The horizontal dotted lines in the conjoined towers are located at the average link height. As can be seen from the figure, while the average height is around two-thirds height of the building, it is somewhat lowered when the number of link structures is increased. The average heights based on the studied cases are 71%, 67% and 63% height for the towers with one, two and three/four link structures respectively.

In order to present the impact of increasing the number of link structures, Figure 10 plots comparative maximum lateral displacements at the top of the 120-story superframed conjoined towers with no, one, two, three and four link structures shown in Figure 9. As can be seen from the figure, the impact of initially placing one link is significant in terms of increasing lateral stiffness. The maximum lateral displacement is reduced by 43% by adding a link between the adjacent braced tube towers. Subsequently adding an additional link structure further decreases the maximum displacements by 23%, 14% and 11% when the number of link structures becomes one to two, two to three, and three to four, respectively.

3.4. Dynamic Properties of Superframed Conjoined Towers

Dynamic properties of the superframed conjoined towers

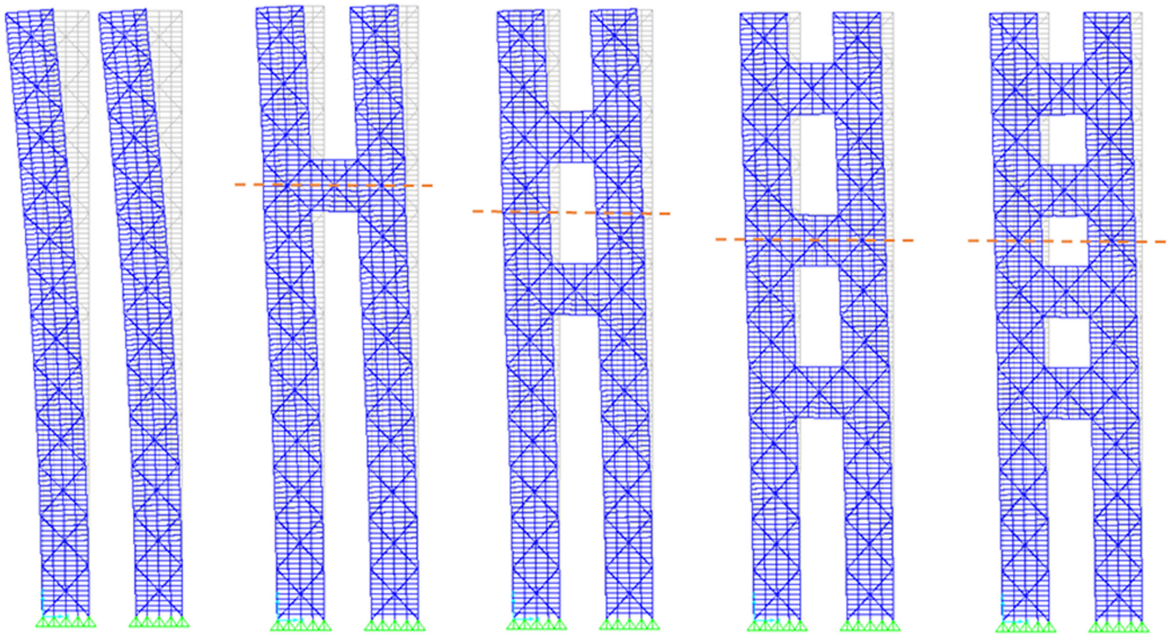


Figure 9. Wind-induced deformed shapes of 120-story superframed conjoined towers with no, one, two, three and four link structures at their better locations in terms of lateral stiffness. (deformation is exaggerated by a scale factor of 30 for clarity)

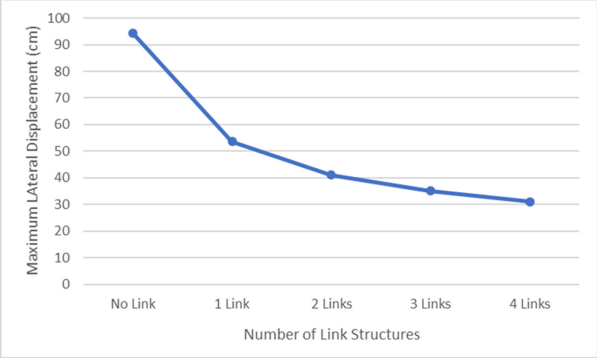


Figure 10. Maximum lateral displacements at the top of 120-story superframed conjoined towers with no, one, two, three and four link structures shown in Figure 9.

are also very important design considerations. As the lateral stiffness of the superframed conjoined towers is increased compared to that of the solo braced tube, the lateral translational modal periods are shortened in the conjoined towers. The periods of the fundamental mode are 9.09 and 7.52 seconds for the 120-story solo braced tube and superframed conjoined towers respectively. However, unlike the lateral translational modal periods, torsional modal periods are longer in the superframed conjoined towers due to the greater mass. The first torsional modes of the solo braced tube and superframed conjoined towers respectively are 3.17 and 5.79 seconds.

It is also noted that in the superframed conjoined towers, there are conjoined-tower-specific unique modes not found in the solo tower. Some modes of the superframed conjoined towers are primarily based on the dynamic responses of the protruded tower portions above the link level. Examples of these cases include the 4th through 8th modes. Figure 11 shows the 1st, 3rd, 5th, 7th and 9th mode shapes of the 120-story superframed conjoined towers composed of four braced tubes. Among these, 3rd and 5th mode shapes are conjoined-tower-specific as explained. No modes of the solo braced tube are comparable to these conjoined-tower-specific modes. As the vortex-shedding induced lateral vibration is one of the most critical design considerations for the structural design of tall buildings, studies on the dynamic properties of the superframed conjoined towers are essential.

4. Design Applications of Superframed Conjoined Towers

While the concept of superframed conjoined towers can produce feasible and more sustainable design solutions for megatall building complexes, there are no built examples yet. Design studies applying the concept have been carried out by graduate students guided by the author at the Yale School of Architecture. Chicago's lakefront site that was once used for the Chicago Spire design project by Calatrava and the adjacent empty site are used together for the design studies.

4.1. Superframed Conjoined Towers with Four Linked Megatall Buildings

In the design project carried out by Fuchs and Miranda, 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. 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.

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

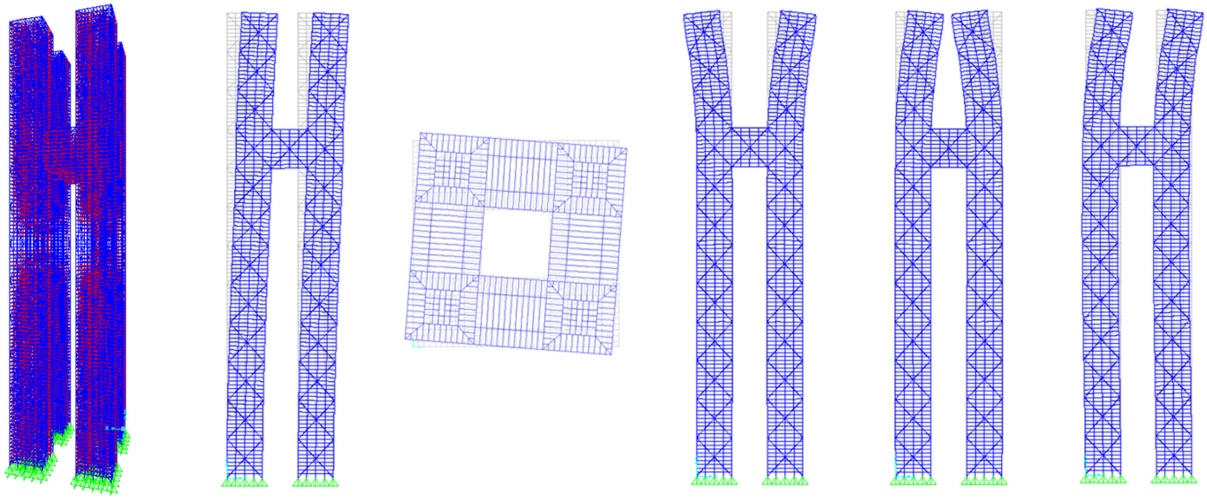


Figure 11. 3D view and the 1st, 3rd, 5th, 7th and 9th mode shapes of the 120-story superframed conjoined towers composed of four braced tubes. (3rd mode in plan view; other modes in elevation view)

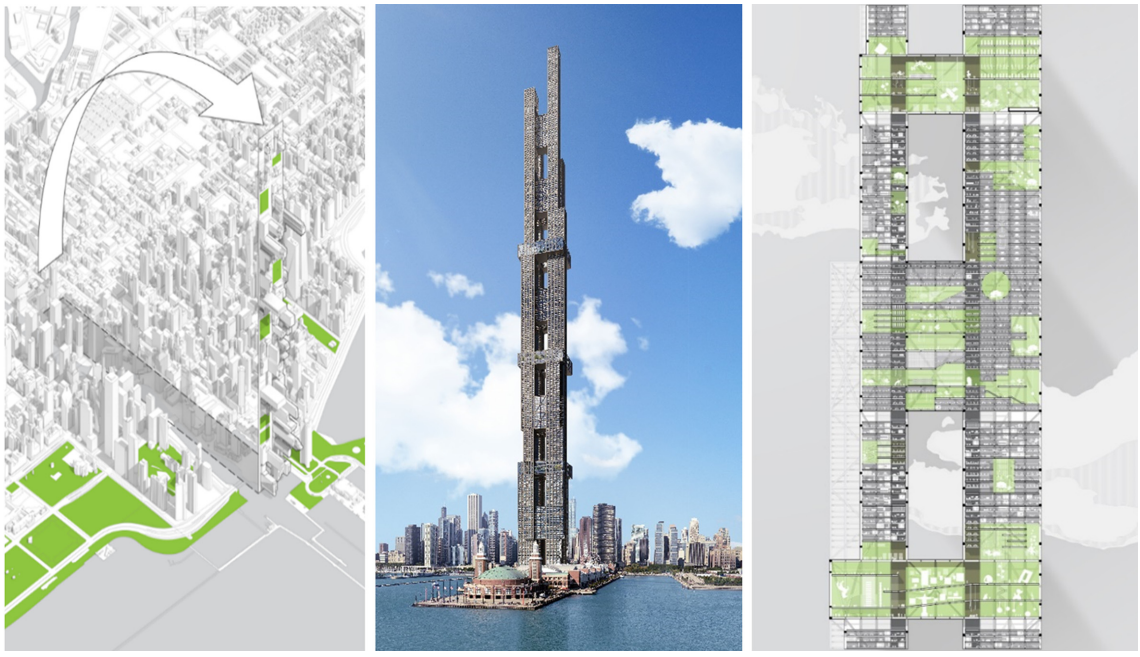


Figure 12. Mile-high superframed conjoined towers at Chicago lakefront: design concept (left), rendering (middle) and partial section (right). [Design by Fuchs and Miranda].

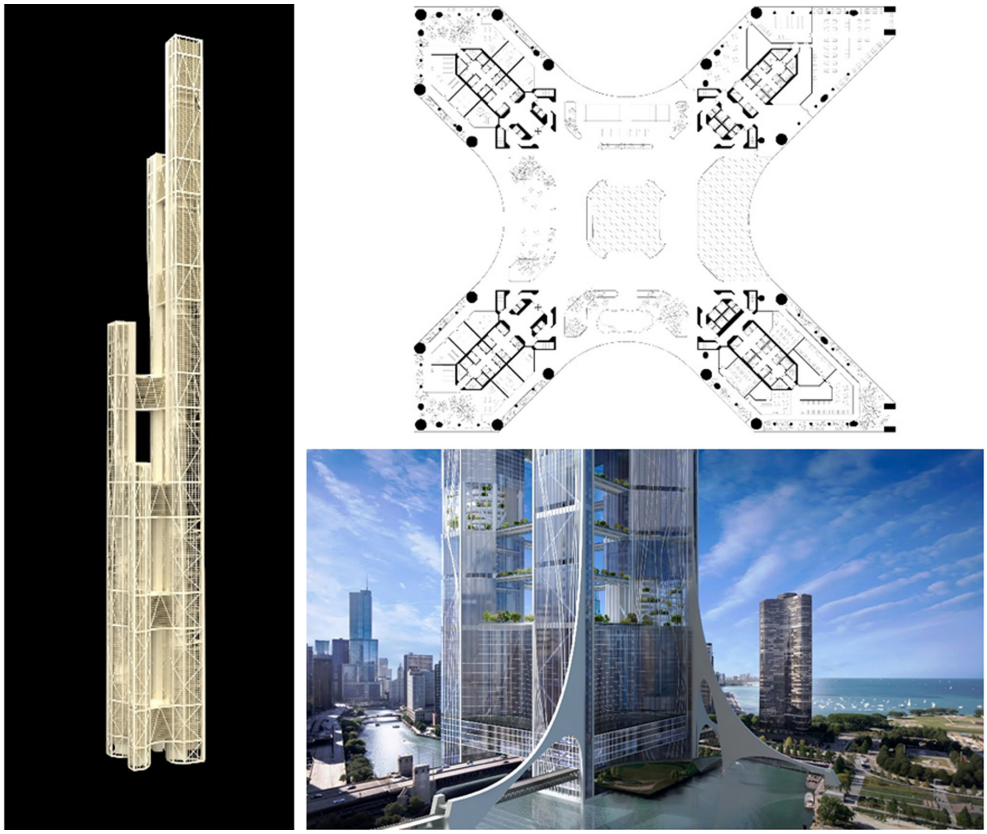


Figure 13. Vertical Chicago: structural model (left), typical floor plan (upper right) and partial rendering (lower right). [Design by Cui and Dong]

of the tower complex against wind loads through 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 as discussed earlier.

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 as can be seen in the section in Figure 12.

In the "Vertical Chicago" developed by Cui and Dong, the concept of the superframed conjoined towers is also employed to design a self-contained vertical city-like tall building complex. Four megatall buildings of different heights are structurally connected at multiple levels. The tallest tower reaches the height of one mile. Multistory link structures contain sky lobbies and communal spaces serving for the complex. In this project, braced megatube structures that are better integrated with architectural design of this scheme are used for individual towers and they are interconnected by horizontal braced megatubes.

A critical design issue in the superframed conjoined towers composed of four clustered towers is blocking views from the two sides of each tower when the four towers of square floor plan are arranged to form again square plan for the whole complex. In order to resolve this issue, each tower's floor plan is designed as elongated hexagonal forms in the Vertical Chicago (Figure 13). In addition, by placing the core of each tower at an appropriate corner so that all cores are toward the center of the combined floor plan of the complex, the blocking view issue can significantly be resolved.

4.2. Variations of Superframed Conjoined Tower Concept

When designing cojoined towers, joining only two towers may result in a unique design challenge compared to joining three or more towers. When only two towers are conjoined, structural depth against wind loads can be larger only in the direction parallel to the link structure. Therefore, the important structural benefit of conjoining tower structures can be limited.

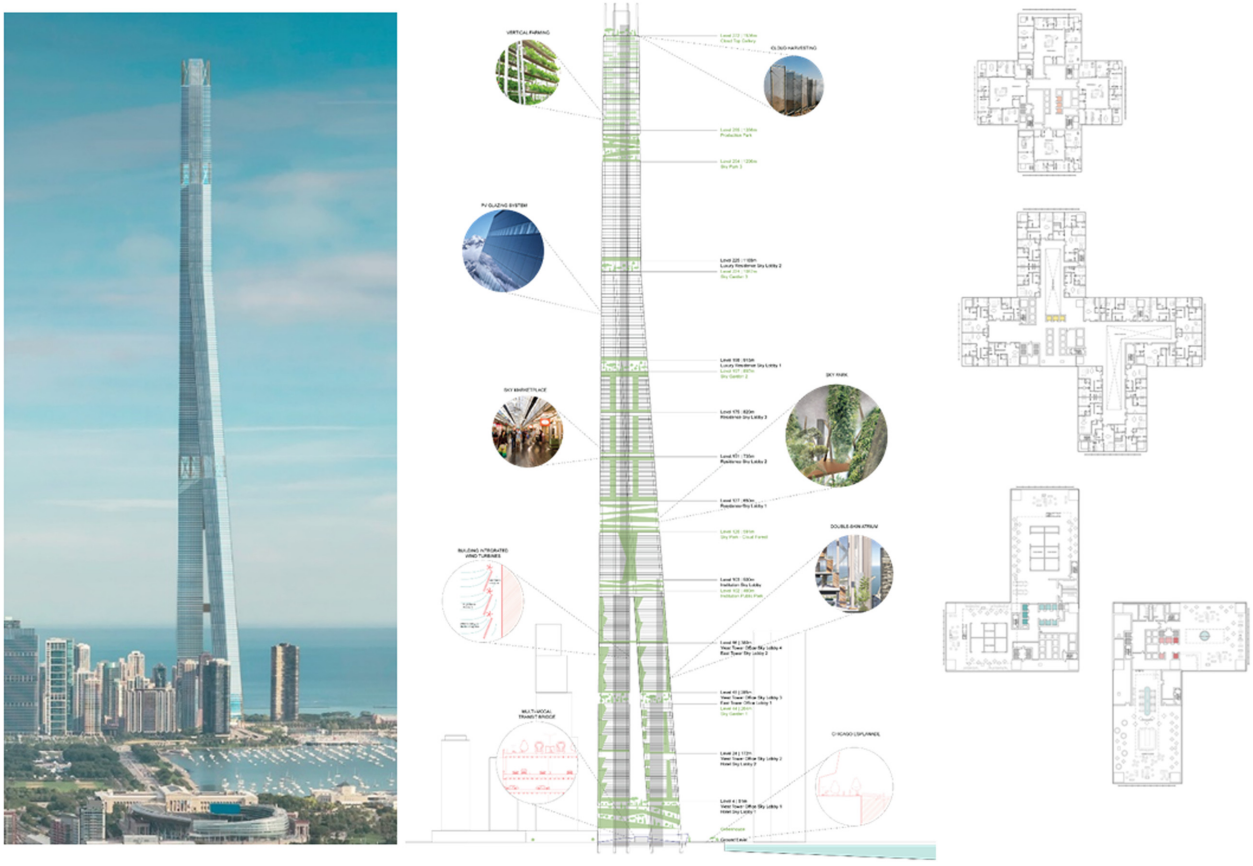


Figure 14. Structurally linked conjoined towers with two merging megatall buildings: rendering (left), section (middle), and typical floor plans (right). [Design by Ching and Shen]

In the mile-high tower project by Ching and Shen shown in Figure 14, the lower part of the tower is composed of two separate L-shaped floor plans. The structural depths against wind loads of each L-shaped floor plan are different in the x and y direction. However, when the two floor planes are considered together, the structural depths of the combined floor plans in the two directions are identical. Indeed, the floor plans are configured in this way because the two floor plans are merged toward the higher levels. By adjusting the wing lengths of the two L-shaped floor plans while merging, they eventually become a Greek cross shape plan at the topmost floors.

Both structural and architectural design were considered carefully for this design. The project uses a rectangular site separated approximately in the middle by the Lake-shore Drive in Chicago. Therefore, the lower part of the building is separated according to the site condition. However, in order to use the structural benefit of conjoined towers in terms of structural depth against wind loads, the separate buildings on their lower levels are structurally conjoined from around the mid-height of the building. And large communal spaces are produced as the two towers merge.

While the previous design is complete with two conjoined towers as one tower leans on and merges with the other for the benefits of both towers, the conjoined towers proposed by Liu and Xu is designed with the concept of expandability. The project as shown in Figure 15 is composed of six megatall buildings interconnected at multiple levels. While the project at its initial stage is complete with these six towers, the overall configuration of the design is to better accommodate future growth.

For better expandability, each tower's floor plan is circular, and towers are clustered to form equilateral triangles with three of them. In this way, the complex can easily be expanded and interconnected as can be seen in the figure. In order to obtain more flexibility in facade

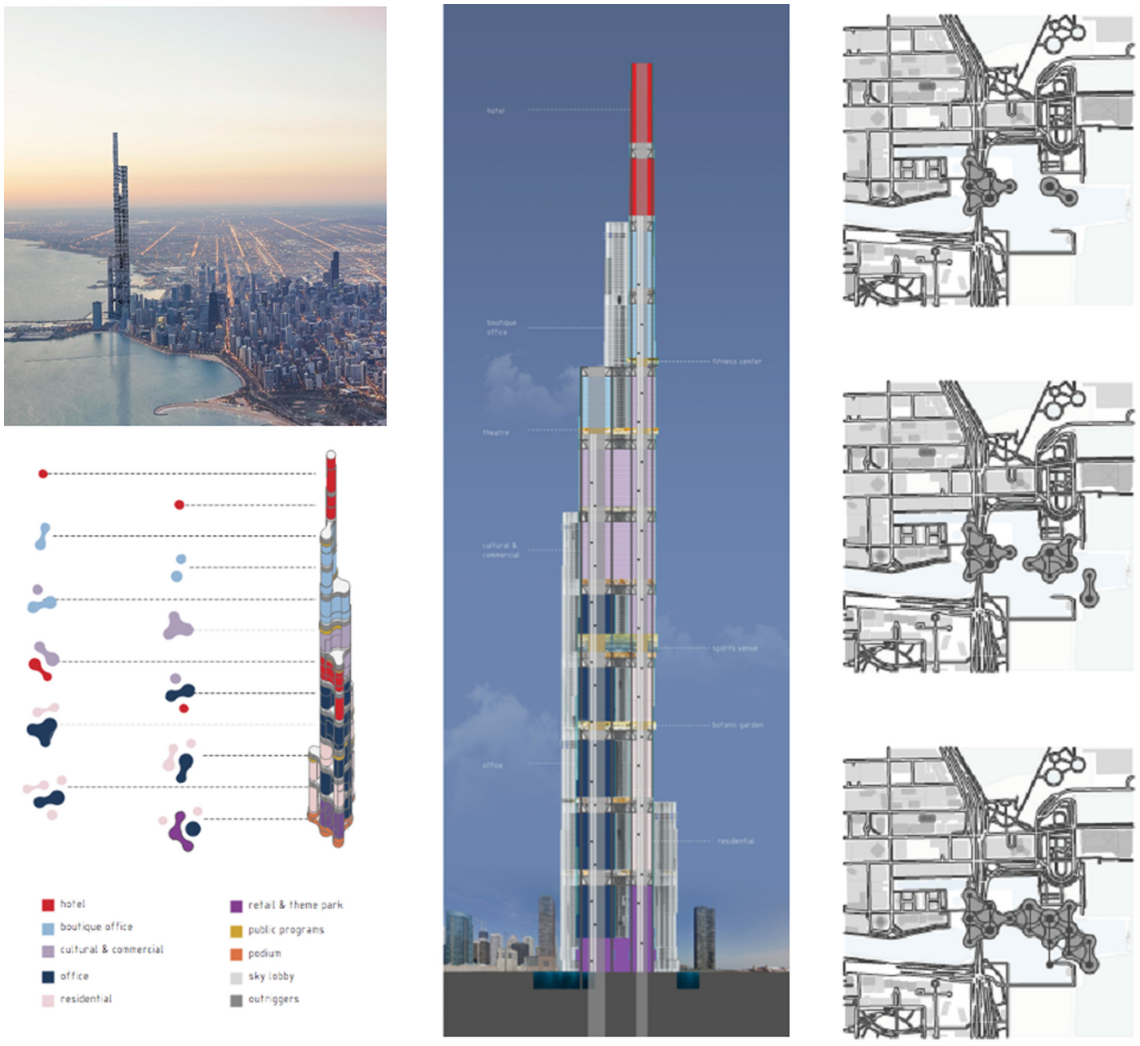


Figure 15. Expandable conjoined towers: rendering and program (left), section (middle) and future expansion diagram (right). [design by Liu and Xu]

design and better interaction between the towers at link levels, core-outrigger system is used for each tower and interconnected by trusses at the outrigger truss levels. This design project is carried out as the first phase of multi-phase developments.

5. Conclusion

Since the emergence of tall buildings in the late 19th century, they have typically been developed as solo towers. Though conjoined towers have also been built occasionally since the early 20th century, they have not been on the mainstream of tall building developments and their full potentials have rarely been explored.

Tall buildings are an essential building type to accommodate ever increasing urban population and it is expected that the heights of tall buildings will continuously be increased. Unlike other building materials, the required amount of structural materials is increased exponentially as a building becomes taller to provide adequate stiffness against lateral loads. Therefore, it is important to employ more efficient structural systems to build tall buildings with less amounts of structural materials coming from our limited natural resources. As a feasible design concept for this purpose, this paper has presented superframed conjoined towers and their performances in comparison with solo towers.

Another critical design issue of solo tall buildings is that it has a limitation in promoting social sustainability in terms of enhancing interactions between people in the building. This is based on the inherent characteristics of solo tall buildings composed of numerous vertically stacked floors. In the proposed superframed conjoined towers, the linked floors between the towers can provide great opportunity to be designed as very large and dynamic communal spaces that are not available in solo towers and promote occupants' interactions based on more natural horizontal circulations.

The occasionally built conjoined towers have usually been with simple skybridges for circulations between the towers. Exploring more structural and architectural potentials of conjoined towers is still in its early stage. While this paper has presented some early research results on the superframed conjoined towers as a feasible design concept to create more sustainable megatall buildings, further investigations are required to explore their potentials to a greater extent.

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