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Evolution of Tall Building Structures with Perimeter Diagonals for Sustainable Vertical Built Environments

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Abstract Tall buildings are built with an abundant amount of materials, including structural materials, coming from our limited natural resources. Tall buildings that began from about 10-story tall office towers have evolved to over 150-story tall mixed-use megastructures. As a building becomes taller, structural material requirement to resist lateral wind loads becomes exponentially larger. Therefore, it is crucial to employ efficient structural systems and optimize their design, which will contribute to sustainable vertical built environments through preservation of resources. Tube type structures with large perimeter diagonals are among the most efficient structural systems for tall buildings. Developments of braced tube, braced megatube, diagrid structures, and their optimal design strategies are reviewed. Superframed conjoined towers, produced by interconnecting multiple clustered braced tubes, are presented as a new design direction to achieve not only structural but also architectural and social sustainable design goals.

Keywords Tall buildings, Braced tubes, Braced megatubes, Diagrids, Superframed conjoined towers, Sustainable structural design

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1. Introduction

Early tall buildings in the late 19th century were structured with iron skeletons in their interiors and masonry walls on their perimeters in many cases (Condit, 1952, 1961; Landau & Condit, 1996). Therefore, it seriously lacked potential for taller buildings to come due to the limitation of using masonry structure. A break-through occurred when the 10-story tall Home Insurance Building of 1885 in Chicago designed by William Le Baron Jenney employed skeletal frames for not only its interior but also its streetfront walls (Jenney, 1885, 1889, 1891; Tallmadge, 1931, 1934, 1939).

With the development of skeletal frame structures for tall buildings, the efficiency of adding diagonal bracings to the orthogonal frames were also recognized to resist lateral wind loads (Landau & Condit, 1996). Consequently, braced frames were widely used for tall buildings including the 102-story tall Empire State Building of 1931 in New York. However, as the braced frames were placed usually around the buildings' interior cores, their structural efficiency was not maximized as their structural depths against wind loads were limited to the widths of the cores.

Another significant structural breakthrough occurred in the 1960s when the tubular structure was developed. By placing lateral load resisting systems on the buildings' perimeter, their structural depths are maximized in the tubular structure, and more efficient structures are created for tall buildings (Khan, 1970, 1972, 1973, 1974). Among various tubular structures, those with large perimeter diagonal bracings, such as braced tubes and relatively recently used braced megatubes and diagrids, are typically more efficient than those without diagonals (Moon, 2007, 2010, 2012). This is because the tube type structures with large perimeter diagonal bracings carry lateral shear forces primarily by axial actions of the diagonals. Efficient structural engineering against wind loads results in using less structural materials to construct tall buildings. Considering gigantic scales of tall buildings that require immense amounts of structural materials coming from our limited natural resources, the contribution of efficient structures to the construction of sustainable built environments is significant.

When a particular structural system is selected for a tall building, its detailed configuration has a very large impact on the efficiency of the system. The detailed configurations include geometric configuration and stiffness distribution along the height of the building. This paper also discusses the impacts of these detailed configurations on structural efficiency of tall buildings.

When a building becomes taller, the required amount of most building materials becomes more or less proportionally greater, whereas that of structural materials to produce

adequate lateral stiffness against wind loads becomes exponentially larger due to the "premium for height (Ali, 2001; Khan, 2004; Ali & Moon, 2007, 2018)." This means that the importance of efficient structural design becomes even more critical as tall buildings become ever taller. Therefore, it is crucial to employ more efficient structural systems and configurations as well as corresponding design optimization strategies for material-saving sustainable engineering of tall buildings. Using less material also means reducing embodied energy for the chosen material. While emphasis is placed on structural efficiency toward sustainable engineering, other related design aspects are also discussed holistically in this paper.

Many tall buildings throughout the world have been designed and constructed as solo towers. Consequently, developments of more efficient tall building structural systems have mainly been for solo towers. However, some tall buildings have been developed as interconnected tower complexes. In fact, conjoined towers have great potentials to overcome some of very critical design issues of solo towers. This paper also explores a more efficient structural solution for interconnected towers with the concept of superframed conjoined towers composed of multiple braced tube structures.

2. Braced Tubes and Braced Megatubes

2.1. Braced Tubes

In tall buildings, it is very important to increase their structural depths against wind loads to produce more efficient structures. This leads to saving structural materials for tall buildings of enormous scales. The structural depth is maximized in tubular structures by placing lateral load resisting systems on the building perimeter. To begin the discussion on tubular structures, a solid tube vertically cantilevered from the ground can be considered first. While this could be a very efficient structural system for tall buildings, without fenestrations, a windowless solid tube cannot perform architecturally. Therefore, to meet both structural and architectural design requirements, openings are essential on the perimeter.

A convenient shape to make openings in buildings is rectangles. To produce a tube structure with rectangular openings, narrowly spaced vertical columns and deep spandrel beams orthogonal to the columns can be placed on the building perimeter. Then, a framed tube structure is created as was the case with the demolished World Trade Center twin towers in New York. While the framed tube is an efficient structural system for tall buildings, its performance is not ideal because the behaviour of the orthogonal tube-composing frames on the web planes (planes parallel to winds) involves rigid frame actions. This means that the lateral load-carrying mechanism involves bending of the columns and beams. Apparently, carrying loads by bending of structural members is not an efficient way. The orthogonal configuration also results in larger shear lag effect in the framed tubes than other tube type structures discussed in this paper.

Once large diagonal members are added in the orthogonal exterior frame, a braced tube is produced. A braced tube is a three dimensional vertically trussed tube. Compared to the structural efficiency of the framed tube composed of orthogonally arranged perimeter columns and spandrel beams, that of the braced tube of triangulated configuration is substantially larger. This is because, unlike the framed tubes, lateral shear forces are carried primarily by axial actions of the diagonal bracing members on the web planes in the braced tube. Axial action is generally much more efficient load-carrying mechanism than bending action. With the great shear rigidity provided by trussed web frames, bending moments caused by the wind-induced overturning moments are also carried very efficiently primarily by axial actions of the perimeter columns on the flange planes (planes perpendicular to winds).

Another tube configuration developed as a more efficient structure than the framed tube is a bundled tube. The shear lag effect is reduced by placing additional web frames within the perimeter tube structure as in the case for the Sears Tower of 1974 in Chicago. Nonetheless, the braced tube is still more efficient than the bundled tubes because the lateral loads are almost entirely carried by axial actions of the perimeter tube members.

Table 1 shows comparative structural efficiency between these three structural systems. As can be seen in the table, the braced tube with perimeter diagonals employed in the John Hancock Center is more efficient than the other two tube structures with no diagonals. In terms of the amount of steel used per unit floor area based on the available data for these three supertall buildings of relatively similar heights and height-to-width aspect ratios, the bundled tube uses about 10% less steel than the framed tube; the braced tube uses about 10% less steel than the bundled tube. The amount of structural steel used per unit floor area is substantial, ranging from 145 kg/m^2 in the braced tube to 181 kg/m^2 in the framed tube (Schueller,

Table 1. Amount of steel used per unit floor area (Source: Schueller, 1990)

Building	Year	Stories (Height/Width)	Gross Building Area	Structural System	Steel Used per Unit Floor Area
John Hancock Center, Chicago	1969	100 (7.9)	260,100 m^2	Braced Tube	145 kg/m^2 (29.7 psf)
WTC (Demolished), NYC	1972	110 (6.9)	400,000 m^2	Framed Tube	181 kg/m^2 (37.0 psf)
Sears Tower, Chicago	1974	109 (6.4)	423,600 m^2	Bundled Tube	161 kg/m^2 (33.0 psf)



Figure 1. World Trade Center in New York City. (Demolished; Typical Column Spacing: 1 m; Photo Source: Wikipedia); Sears Tower in Chicago (Typical Column Spacing: 4.5 m; Photo Source: Wikipedia); John Hancock Center in Chicago (Typical Column Spacing: 12 m; Photo Source: Kyoung Sun Moon)

1990). As the gross floor areas of these buildings are extremely large, ranging from about a quarter to almost a half million square meters, the impact of selecting a particular structural system for a tall building in terms of structural material use is significant.

Figure 1 shows the facades of the three tall buildings compared in Table 1. It can be observed that more efficiently configured tube structures can be designed with wider column spacings. However, it should also be noted that the widest column spacings of about 12 m (40 ft) among the three was achieved by placing large perimeter diagonals on the perimeter, which might not always be welcomed architecturally.

2.2. Braced Megatubes

In typical braced tubes, evenly spaced multiple perimeter columns are placed on flange and web planes (planes perpendicular and parallel to winds, respectively). Wind-induced overturning moments are primarily carried by axial actions of the perimeter columns on the flange planes as well as those on the web planes except those on the neutral axis. When a rectangular floor plan is considered, the columns on the flange planes generate overturning moment-resisting couples with the maximized moment arm of the building width. However, the contribution of the columns on the web planes to resist overturning moments is limited as the couple moment arm is reduced for the columns closer to the neutral axis.

To maximize the efficiency of perimeter columns in terms of resisting overturning moments in braced tube structures of rectangular floor plans, only four corner megacolumns can be used instead of evenly spaced multiple columns on every side (Khan, 1972; Rastorfer, 1985). By placing only four corner megacolumns, bending rigidity against overturning moments can be maximized because all columns are placed with the maximized resisting couple moment arm. This modified and structurally enhanced version of the braced tube is categorized as a braced megatube to distinguish it from the traditional braced tube with regularly spaced multiple columns on every façade plane (Ali & Moon, 20018). Indeed, the concept of the braced megatube was conceived by Fazlur Khan around the time when he designed the first braced tube structure for the John Hancock Center of 1969 in Chicago though actual application of the braced megatube is for recent supertall buildings. Khan, however, laid down the underlying principle of this structural system.

"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. Logically, this can be arrived at simply. The moment of inertia and the effective section modulus of the entire tubular characteristic of the building are successively increased from the trussed tube (John Hancock) type to megastructure type truss tube, and finally to the four-corner column type truss tube. This then is the ultimate high-rise steel building. It means that at every 20 floors or so there would be transfer trusses both on the exterior and interior of the building, thereby guaranteeing that all gravity loads in the building flow into the four corner columns." (Khan, 1972)

Figure 2 shows three braced tubes of different column spacings as well as a braced megatube to evaluate their performances comparatively (Moon, 2018). The braced tubes are 100-story tall with a story height of 3.9 m, and their plan dimensions are 54 m × 54 m. In Case 1, all the perimeter columns are spaced evenly at every 9 m. In Case 1.1, the column spacing is gradually reduced from 12 m at the mid-width of each façade plane to 6 m at the building corner, with 9 m between them. In Case 1.2, the column spacing is gradually increased from 6 m at the mid-width of each façade plane to 12 m at the building corner, with 9 m between them. The braced megatube shown as Case 1.3 is conceptually the most extreme version of Case 1.1. It uses four corner megacolumns in

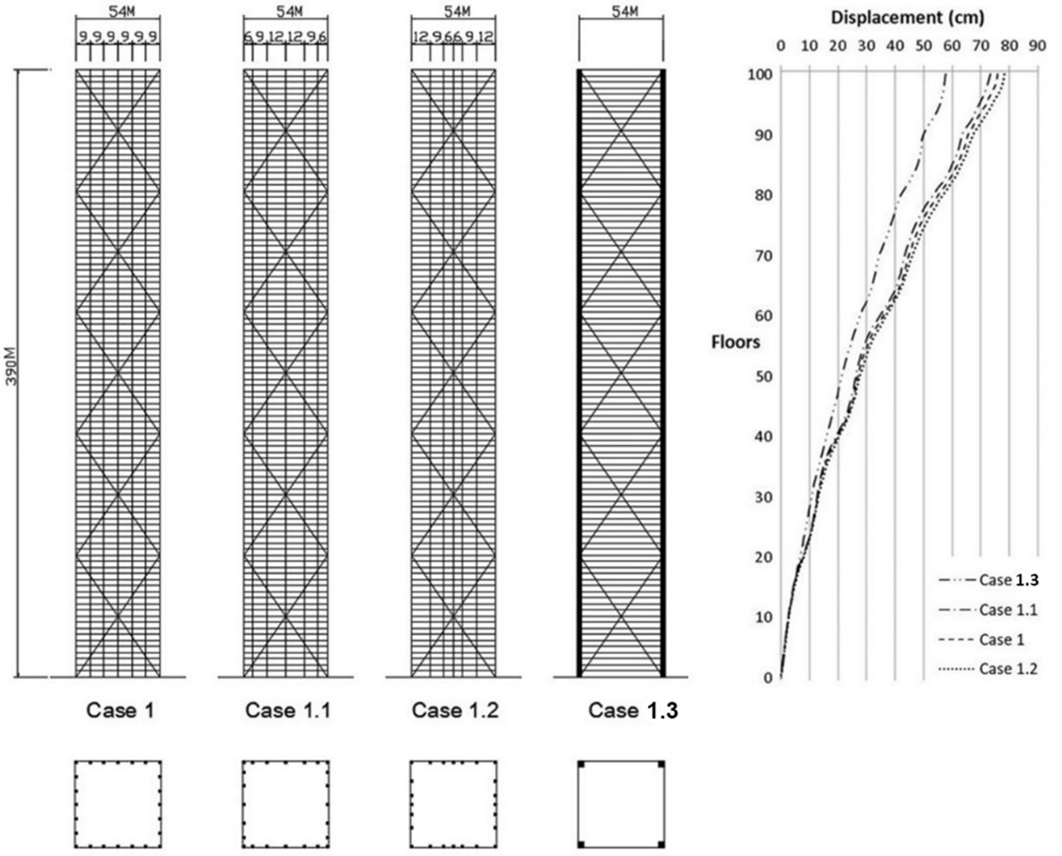


Figure 2. Braced tube structures configured with four different column spacings and their comparative lateral displacements (Source: Moon, 2018)

combination with X bracings between them. The braced tubes are composed of 24 columns. The cross-sectional area of the megacolumns in the braced megatube is six times that of the braced tubes. Therefore, all four cases use the same amount of structural material. The initial design was performed with Case 1 to meet optimally the maximum lateral displacement requirement of a five hundredth of the building height. The structure is assumed to be in Chicago and subjected to the code defined wind loads. As the building is 390 m tall, the maximum lateral displacement is limited to 0.78 m at the top.

The bending stiffness of each case is different because of the influence of the different column configurations, while each case's shear stiffness is almost the same because the configuration of the bracing is unchanged. As the column spacing becomes denser toward the building corners, the contribution of the columns on the web planes to the bending rigidity increases, and vice versa. When four corner megacolumns are used eventually, the bending rigidity is maximized, and, consequently, the lateral displacement of the braced megatube is smaller than any other braced tube cases as can be seen in Figure 2.

To meet the same target displacement requirement, about 23% reduction in structural steel use can be achieved in Case 1.3 when compared to Case 1. As the building becomes taller and slender the comparative structural material reduction becomes even greater due to the "premium for heights." Considering gigantic scales of these structures, this leads to significant saving of materials coming from our limited resources.

Though Case 1.3 provides greater lateral stiffness based on higher bending rigidity, however, a critical design issue of this type of configuration is that it requires a far more challenging gravity load resisting system. This is because the dead and live loads of the floors must be carried also primarily by the four corner megacolumns spaced at 54 m in this particular case. The maximum 54 m is a challenging length to span efficiently. Therefore, gravity columns are added between the megacolumns typically in real world projects. Furthermore, transfer trusses, which transfer the loads from the gravity columns to the corner megacolumns, are placed at each braced megatube module usually defined by the height of the diagonal bracing as can be seen in the Goldin Finance 117 in Tianjin (Figure 3).

There also is an architectural design-related issue. While the braced megatube is one of the most efficient lateral load-resisting systems, its corner megacolumns could be obstructive for viewing from the interior corner spaces, often the most coveted places within tall buildings.

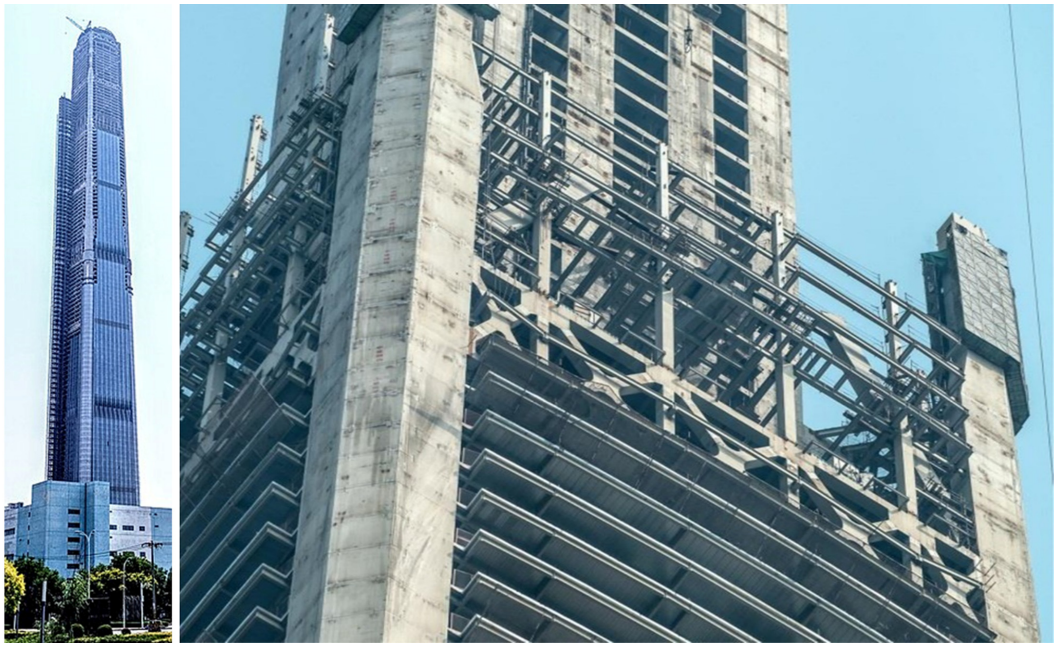


Figure 3. Braced megatube used in Goldin Finance 117 showing corner megacolumns and gravity columns/transfer trusses between them. (Source: Wikipedia)



Figure 4. CITIC Tower during construction showing single corner megacolumns on several lowest levels and split corner megacolumns on typical levels (Source: Wikipedia)

In the 528-m tall CITIC Tower of 2018 in Beijing, the braced megatube concept was used. However, the corner megacolumns of the CITIC Tower are split into two with some distance between them to provide column-free corner spaces, except for several lowest levels near the base where the maximum overturning moment resistance is required (Figure 4). The configuration with split megacolumns around the corners does not provide the same level of stiffness provided by single corner megacolumns when the same amounts of structural materials are used. However, it can produce more desirable architectural result without sacrificing structural efficiency substantially.

3. Diagrids

Another variation of the braced tube is produced by eliminating all vertical perimeter columns. When all the vertical columns are eliminated from the braced tube, perimeter diagonal members act as both slanted columns and diagonal bracings. Therefore, the diagonal members are usually placed at steeper angles and more densely. Then, diagrid structures are created. Compared to the braced tube with vertical columns and diagonal bracings, the performance of diagrids with no vertical columns is much more sensitive to the angles of the diagrid members. Typically, taller and slender buildings require diagrids placed at steeper angles as these buildings want to behave more as cantilevered bending beams.

Early application of diagrids to a building 13 stories tall occurred also in the 1960s when the braced tube was developed, but diagrids have become a widely used structural system for tall and supertall buildings in recent years, such as the 182-m tall Hearst Tower (Figure 5) of 2006 and 439-m tall Guangzhou International Finance Center of 2010. In terms of structural efficiency, diagrids can be even more efficient than braced tubes for tall



Figure 5. Uniform angle diagrids in the 182-m tall Hearst Tower in New York City (Source: Wikipedia) and varying angle diagrids in the unbuilt 555-m tall Lotte Super Tower proposal for Seoul (©SOM)

buildings whose height-to-width aspect ratios are smaller than about seven. However, the braced tubes tend to be more efficient for very tall buildings with their height-to-width aspect ratios larger than about eight (Moon, 2014). Structural efficiency of diagrids can further be increased by varying diagrid angles according to the structural logic (Moon, 2008; Baker et al., 2009). For example, in the unbuilt 550 -m tall Lotte Super Tower project for Seoul (Figure 5), the diagrid angle becomes steeper toward the base and shallower toward the top where the overturning moments and lateral shear forces dominate, respectively.

3.1. Diagrids of Uniform Angle Configuration

As briefly discussed, diagrids can be configured in uniform angles or varying angles along the height of the building. Figure 6 shows 60-story diagrid structures with a height-to-width aspect ratio of about 6 and having various uniform diagonal angles ranging from 53 to 76 degrees depending on the heights of diagrid modules to evaluate their performances comparatively (Moon, 2007). The building's plan dimensions are 36 m × 36 m, and its typical story height is 3.9 m. Therefore, with three diamond-shaped sub-modules placed horizontally within the building width of 36 m, 4, 6, 8, 10 and 12-story tall diagrid modules result in diagrid angles of 53, 63, 69, 73 and 76 degrees, respectively. The structures are designed in such a way that lateral stiffness is provided only by the perimeter diagrids and core structures carry only gravity loads.

Each structure, assumed to be in Chicago and subjected to the code defined wind loads, are optimally designed to meet the maximum allowable lateral displacement requirement of a five hundredth of the building height. Figure 6 also shows steel masses required for each structure to meet the target stiffness requirement. As can be seen from the figure, the diagrid structure configured with a diagonal angle of 69 degrees meets the design requirement with the least amount of structural steel. As the diagrid angle is deviated from its optimal configuration, structural steel use is increased.

Based on the similar studies with diagrid structures of various heights ranging from 40 to 100 stories, optimal angles of diagrids of different heights and height-to-width aspect ratios were found. The structures' height-to-width aspect ratios range from about 4 for the 40-story diagrids to 10 for the 100-story diagrids. Study results show that an angle of 63 degrees (6-story tall diagrid module) is the near optimal angle for the 40 and 50-story diagrids. For the 60-story and taller diagrid structures, an angle of 69 degrees (8-story tall diagrid module) is the near optimal angle. In fact, the theoretical optimal angle for the diagrids should be increased continuously up to a certain angle as the height-to-width aspect ratio of the building is increased from 4 to 10. In this study, however, the diagrid module heights were determined to have diagrid nodes always meeting with the perimeter beams. And the studied uniform diagrid angles are based on these module heights.

3.2. Diagrids of Varying Angle Configuration

Structural efficiency of diagrids can be further increased for very tall buildings by varying diagrid angles. Incremental rates of shear forces and overturning moments toward the base of a tall building are different. While lateral shear forces increase more or less linearly, overturning moments increase exponentially toward the base of the building. Thus, in a properly designed diagrid structure, the design of the upper portion of the building is governed by shear forces, while the lower portion is governed by overturning moments. Considering this, it can be presumed that diagrid structures with gradually changing diagonal angles shall have potential for greater

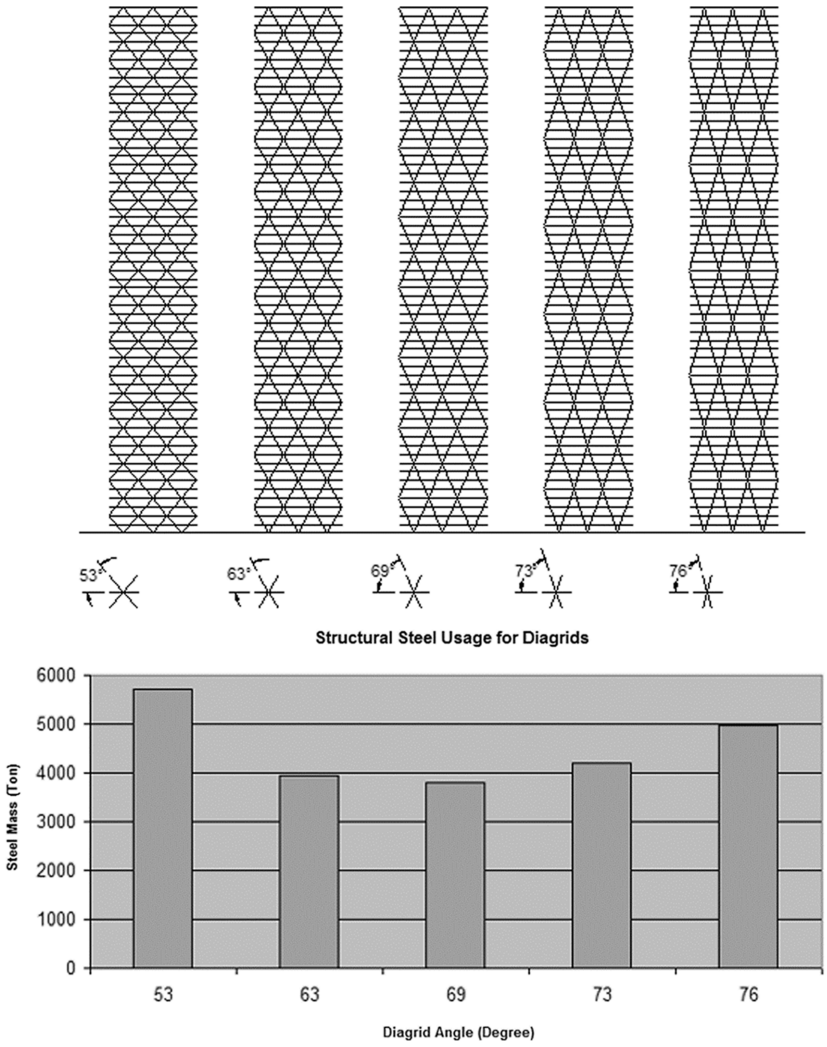


Figure 6. 60-story diagrids of different patterns with various uniform angles and required structural steel for each to meet the same target stiffness requirement. (Source: Moon, 2018)

structural efficiency.

Various varying angle diagrid configurations are shown as examples in Figure 7 for 80-story diagrid structures with a height-to-width aspect ratio of about 8 to evaluate their performances comparatively (Moon, 2008). Notice that Alt. 3 is in fact a uniform angle design with the near optimal angle. Each structure is designed to meet the same maximum allowable lateral displacement requirement of a five hundredth of the building height to find the optimal angle configuration for the diagrid of this height and height-to-width aspect ratio. As can be seen in the figure, varying angle design Alt. 2, which is configured with steeper angle diagonals toward the base, uses the least amount of structural steel for the 80-story diagrids. However, if the angle becomes too steep (Alt. 1), it loses its shear rigidity drastically, resulting in less efficient solution. Alt. 4 and 5 are included for the completeness, but they use more materials than other design alternatives because their grid configurations do not follow the shear and bending moment characteristics of tall buildings.

4. Optimal Lateral Stiffness Distribution for Braced Tube and Diagrid Structures

Structural design of tall buildings is generally governed by lateral stiffness rather than strength (Connor, 2003). A very important design criterion to meet in this context is limiting the maximum lateral displacement at the top of the building smaller than a desired target value. The target value that is usually determined based on the function of the building is in the neighborhood of a five hundredth of the building height (Kowalczyk et al., 1995). Functions requiring more occupant comfort, such as residentials, are designed with a smaller target value, meaning smaller building movements, and vice versa.

There are numerous ways to meet the target displacement requirement for distributing lateral stiffness over the height of a tall building. Two primary modes of wind-induced lateral deformation are bending and shear. When a tall building is considered as a vertical cantilever on the ground, an optimally structured tall building behaves

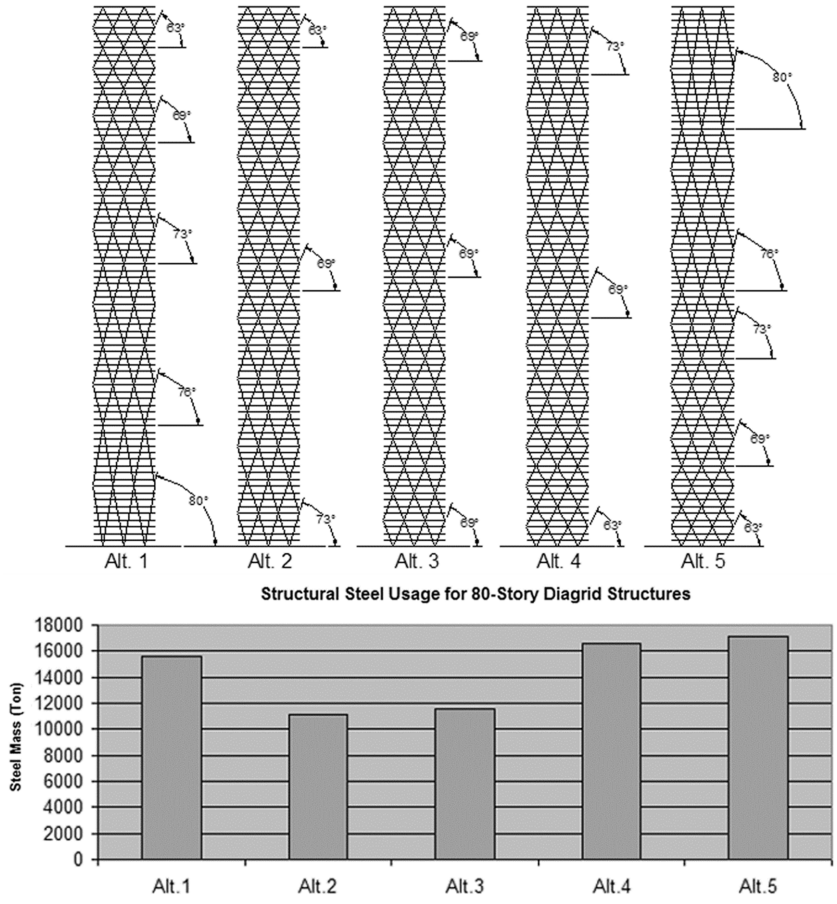


Figure 7. 80-story diagrids of various varying angles and required structural steel for each to meet the same target stiffness requirement. (Source: Moon, 2018)

more as a cantilever bending beam, producing larger bending deformation than shear deformation. The optimal bending to shear displacement ratio is primarily dependent on the building's structural system and height-to-width aspect ratio. Among the previously discussed three very efficient structural systems for tall buildings with large perimeter diagonals, i.e., braced tubes, braced megatubes, and diagrids, for the most efficient structural design, diagrids need to be designed to perform more as a bending beam to the largest degree while braced megatubes to the smallest degree. This means that when the three structural systems of the same height and height-to-width aspect ratio are comparatively considered, for the most efficient structural design for each, the diagrids should be designed to produce the largest bending to shear displacement ratio among the three to meet the target displacement. And the braced megatubes should be designed to produce the least bending to shear displacement ratio among the three.

When bending rigidity is compared between an optimally designed braced tube and diagrid structure of the same height and aspect ratio, bending rigidity provided by vertical columns of the braced tube is much greater than that provided by inclined diagonals of the diagrid. With regard to shear rigidity, there are more diagonal members in the diagrid structure than in the braced tube typically. Thus, the diagrid structure provides greater shear rigidity. Therefore, the optimally designed diagrids produce larger bending-to-shear displacement ratio than the braced tube. Figure 8 shows required steel mass for 100-story braced tube and diagrid structures when various stiffness distributions are used. The value 's' is the ratio of bending to shear displacement at the top. The building's plan dimensions are 36 m × 36 m, and its typical story height is 3.9 m. Each structure, assumed to be in Chicago and subjected to the code-defined wind loads, is designed to meet the maximum allowable lateral displacement requirement of a five hundredth of the building height. The optimal 's' values for the braced tube and diagrids are 4 and 10 respectively, in these cases.

Between the optimally designed braced tube and braced megatube, the braced megatube should be designed with a smaller 's' value than the braced tube of the same height and aspect ratio for optimal design. This is because that bending-to-shear rigidity ratio is larger in the optimally designed braced megatube with corner megacolumns than in the braced tube.

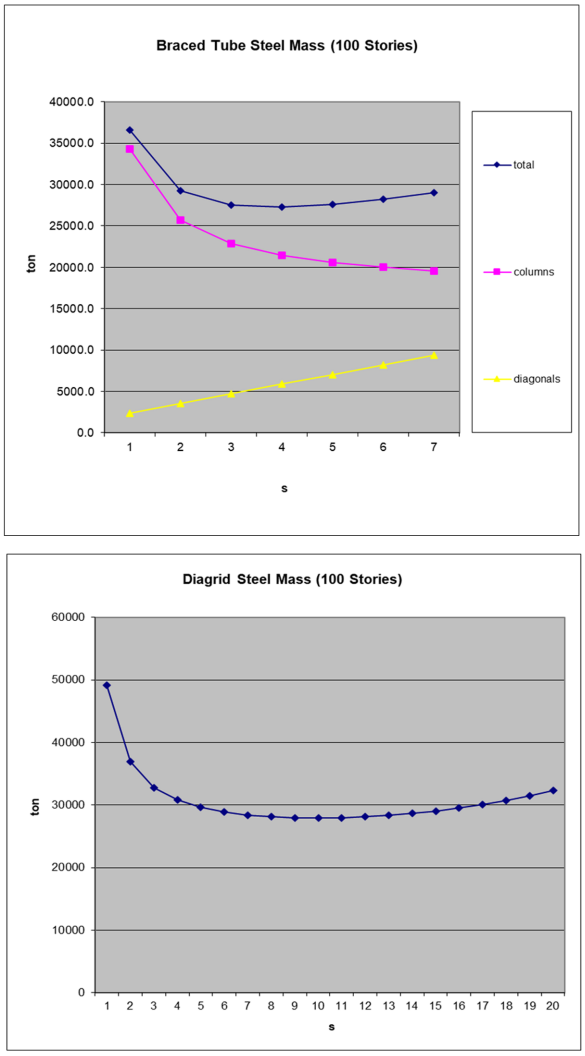


Figure 8. Required steel mass for 100-story braced tube and diagrids when various stiffness distributions are used; 's' is bending to shear displacement ratio. (Source: Moon, 2008, 2010)

5. Superframed Conjoined Towers

Structural systems developed for tall buildings have been for stand-alone solo towers as presented in the previous sections. Therefore, even if very efficient tube type structures with diagonals are used, their structural depths are still limited to the width of a single building. However, oftentimes, multiple tall buildings are designed and 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. This section is on the efficient structural system for these conjoined towers. The concept of superframed conjoined towers is introduced and its performance toward sustainable design is presented. Superframed conjoined towers can contribute to not only material-saving structural engineering but also enhancing social sustainability of tall buildings.

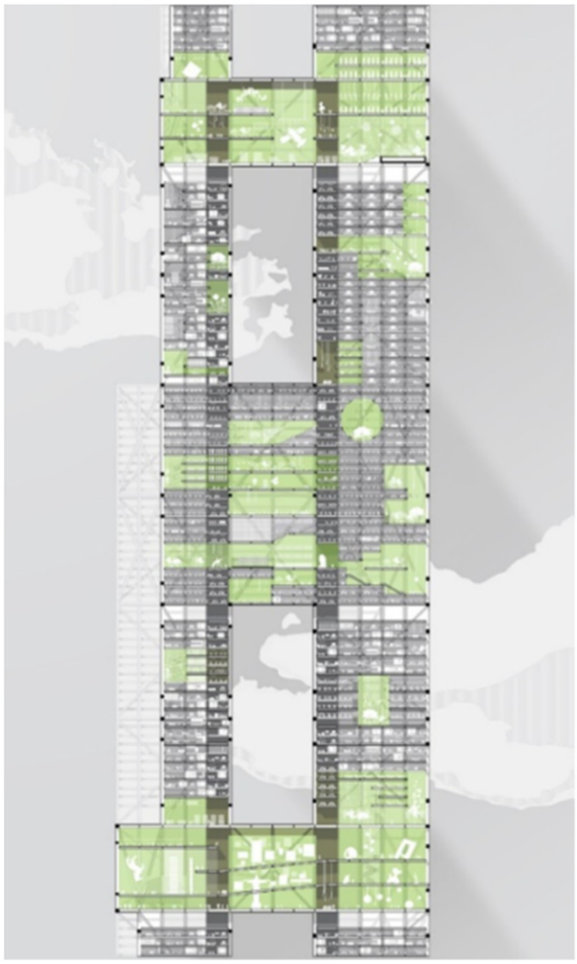


Figure 9. Superframed conjoined towers' section showing variously scaled communal spaces providing enhanced social interactions within the tall building complex. (Source: Moon & Miranda, 2020).

In the superframed conjoined towers, multiple towers are interconnected architecturally as well as structurally. Among the braced tube, braced megatube, and diagrids, the braced tube structure is employed for the individual tall buildings composing the superframed conjoined towers in this study. Further, the braced tube structure is also used for the horizontally bridging structures between the towers.

While all three structural systems discussed earlier in this paper can be used to compose an efficient superframed conjoined towers, as discussed in Section 3, braced tubes and braced megatubes can be more efficient than diagrids for very tall and slender buildings. Therefore, for very tall superframed conjoined towers, braced tubes and braced megatubes are considered comparatively first. While braced megatubes are more efficient than conventional braced tubes for solo towers, the efficiency of braced megatubes are diminished when employed for superframed conjoined towers as explained later in this paper. Therefore, studies on superframed conjoined towers composed of

braced tubes are primarily presented.

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 created. This overall configuration can better resolve the critical architectural and social design limitations of independent tower-based tall building complex developments (Figure 9).

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 as discussed earlier. 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.

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. 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. In the study presented in this section, superframed conjoined towers are composed of four braced tube towers interconnected by horizontal braced tubes.

5.1 Superframed Conjoined Towers with Single Link Structures

When multiple towers are clustered, they are often connected by single link structures between the adjacent towers. While most common cases are connected towers by ground level podium structures, some other cases are connected by single skybridges between the adjacent towers. The structural impact of connecting towers by podium structures is limited. When towers are connected by skybridge structures, however, how and where to connect them are important parameters that can substantially influence the structural performance of the conjoined tower complex.

To investigate the structural performance of superframed conjoined towers with one link structures between the adjacent towers, four braced tube structures of 120 stories are clustered and connected by 10-story tall horizontal braced tube structures (Figure 10), and the code-defined lateral wind load is applied (Moon, 2021). The link structures are placed at 12 different heights by relocating them 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.

Figure 11 shows seven selected cases of the superframed conjoined towers with single link structures, while the maximum lateral displacements at the top of all 12 cases are plotted in Figure 12. As can be observed from

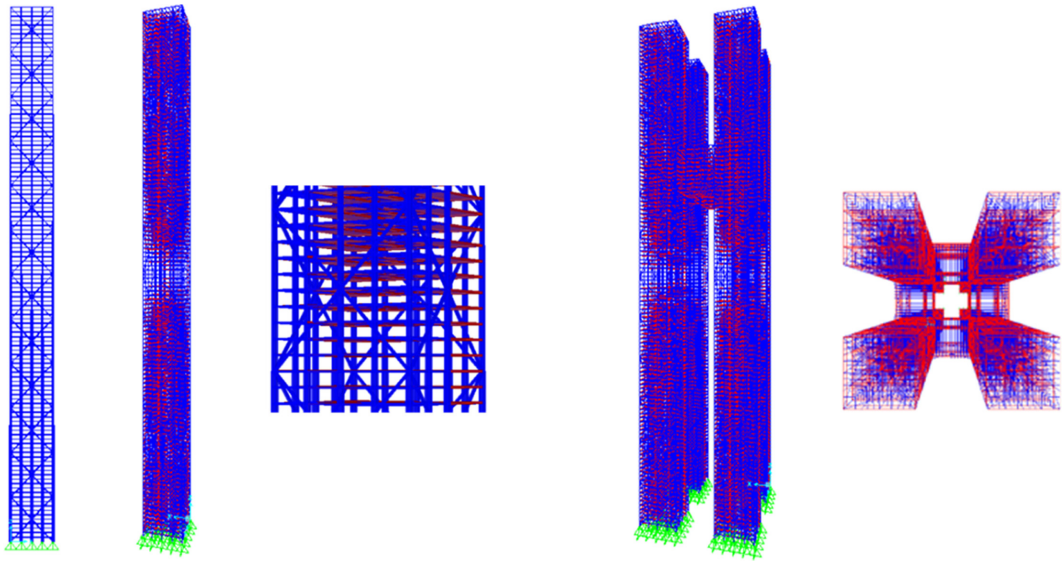


Figure 10. 120-story solo braced tube elevation; 120-story solo braced tube in 3D; 120-story solo braced tube module in 3D (core structure omitted for clarity); superframed conjoined towers composed of the four braced tubes in 3D; Superframed conjoined towers seen from above in 3D

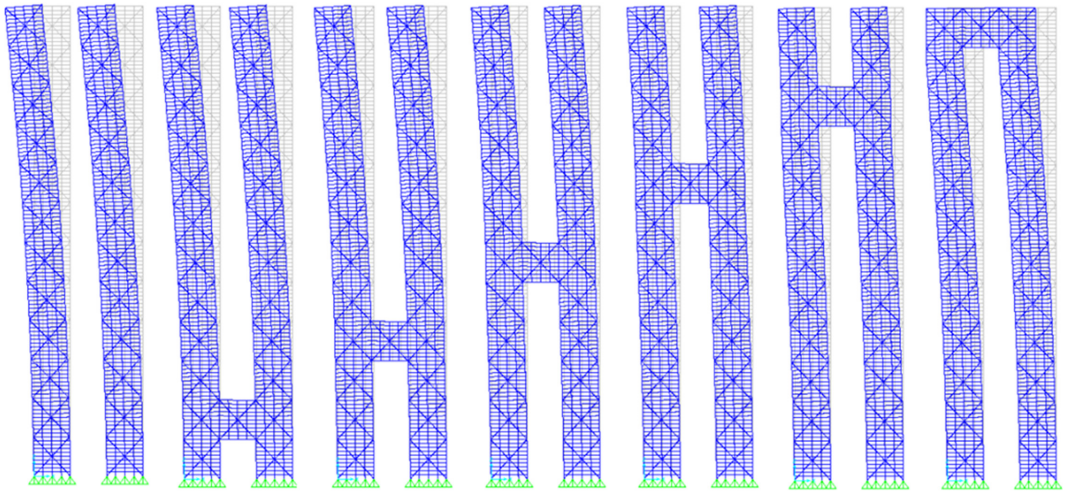


Figure 11. Wind-induced deformed shapes of 120-story superframed conjoined towers with a single link structure at various heights.

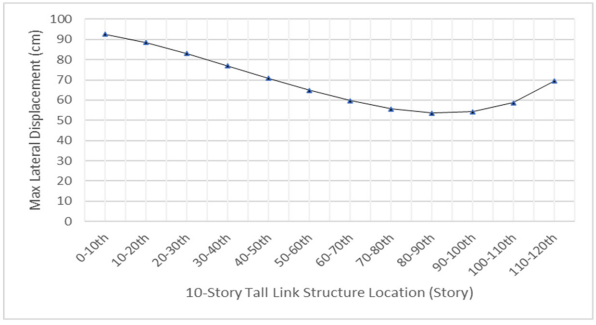


Figure 12. Maximum lateral displacements at the top of 120-story superframed conjoined towers with single link structures at 12 different locations.

the figure, the maximum lateral displacement of 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.

When a very tall solo tower is considered, braced megatube is more efficient than conventional braced tube as discussed earlier in this paper. This better efficiency of the braced megatubes is based on the perimeter columns placed to produce the maximum structural depth effect. However, the efficiency of braced megatubes is diminished when they clustered together to produce superframed conjoined towers because a half of the megacolumns are close to the neutral axes of the conjoined tower plan as can be seen in Figure 13.

Figure 14 shows comparative maximum lateral displacements of the 120-story superframed conjoined towers composed of braced tubes vs. braced megatubes with single link structures at 12 different locations. When link structures are optimally configured, the efficiency of the two cases are very similar.

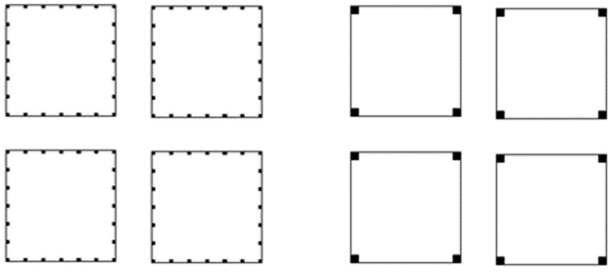


Figure 13. Comparison of perimeter column configurations in plans of superframed conjoined towers composed of four braced tubes and braced megatubes.

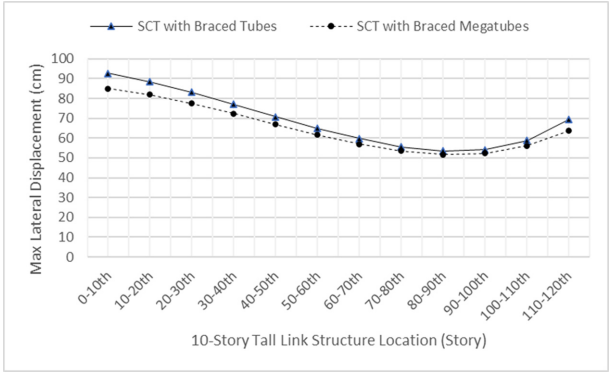


Figure 14. Comparative maximum lateral displacements of 120-story superframed conjoined towers composed of braced tubes vs. braced megatubes with single link structures at 12 different locations.

5.2 Superframed Conjoined Towers with Multiple Link Structures

Studies on the structural performance of superframed conjoined towers are expanded with those with two and three link structures between the adjacent towers. Adding more skybridges further enhance social interactions within the tower complex and increase lateral stiffness of

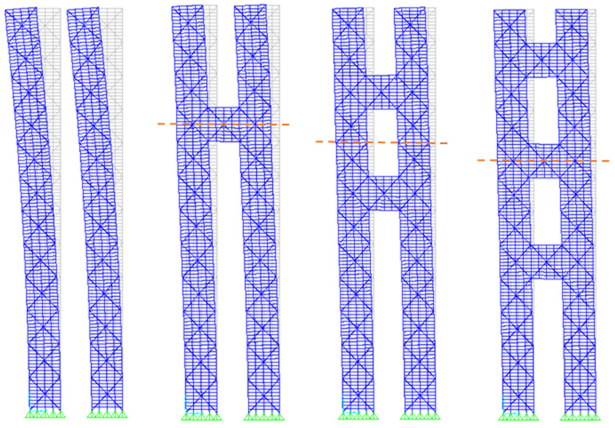


Figure 15. Wind-induced deformed shapes of 120-story superframed conjoined towers with zero, one, two, and three link structures between the towers at their better locations in terms of lateral stiffness.

the superframed conjoined towers. Figure 15 presents wind-induced deformed shapes of the solo braced tube towers and selected best cases with one, two, and three link structures between the braced tubes among many studied alternatives. 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 a bit 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 link structures, respectively.

To present the impact of increasing the number of link structures, Figure 16 shows comparative wind-induced deformed shapes of the four cases shown in Figure 15. As can be seen from the figure, the impact of placing one link between the adjacent towers is significant in terms of increasing lateral stiffness. The maximum lateral displacement is reduced by 43% by adding a link between the braced tube towers. Subsequently adding an additional link structure further decreases the maximum displacements by 23 and 14% when the number of link structures becomes one to two and two to three respectively.

Dynamic properties of the superframed conjoined towers 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. However, unlike the lateral translational modal periods, torsional modal periods are longer in the superframed conjoined towers due to the greater mass. 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. As the vortex-shedding induced lateral vibration is

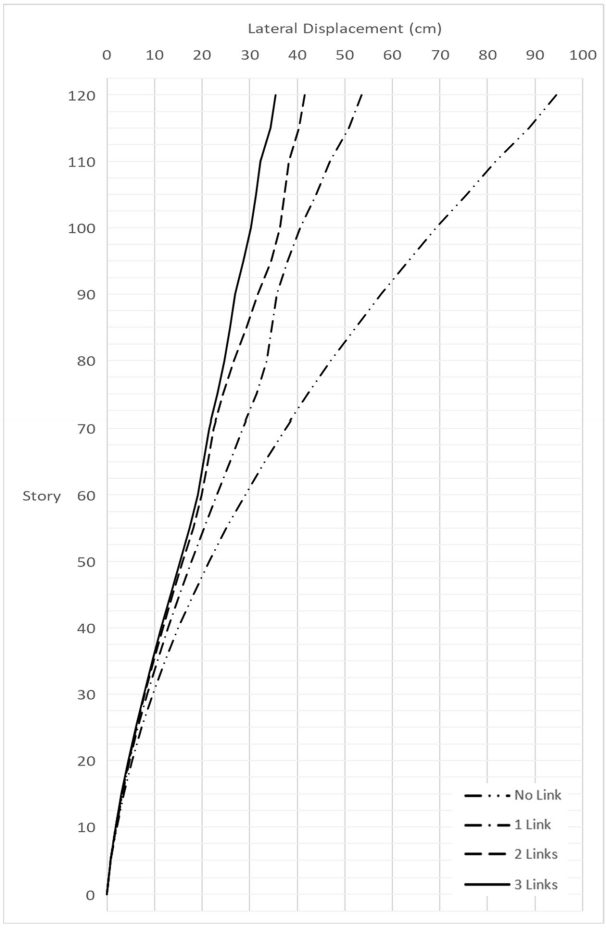


Figure 16. Comparative deformed shapes of the four superframed conjoined towers with no, one, two, and three link structures between the towers shown in Figure 15 subjected to code-defined wind loads.

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.

6. Conclusion

Tall buildings are constructed with enormous amounts of materials coming from our limited natural resources. As a building becomes taller, the required amount of structural materials is increased exponentially to provide adequate stiffness against lateral loads. As it is expected that more supertall, megatall, and even height-record-breaking buildings will continuously be built, employing or developing more efficient and innovative structural systems requiring less amounts of structural materials is very important. Further, optimally configuring the systems is also critical to maximize their efficiency.

Recognizing their outstanding efficiency, this paper has presented tall building structural systems with large perimeter diagonals. Conventional braced tubes have been used for decades and therefore ample related data and

research outputs are available. Nonetheless, studies have been continued for better optimization. Though their inception is also decades ago, diagrid structures and braced megatubes are relatively newly employed systems that still require more investigative works. Structurally coupled conjoined towers are one of the newest systems that need further explorations in terms of their structural, architectural, social, and urban potentials.

Structural developments for tall buildings have been remarkable since their emergence in the late 19th century. Indeed, their main trajectory toward enhanced efficiency initially for more economical solutions has also been in line with sustainable design through saving structural materials. Today, the importance of sustainable design is valued more than ever. As tall buildings are continuously built and they become ever taller, more investigative work, design research and practices for enhanced sustainability are essential.

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