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Structural Design and Performance of Braced Magatubes for Supertall Buildings

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Abstract Among various tubular systems developed for tall buildings, braced tubes with perimeter columns and large diagonal bracings can provide one of the most efficient structural solutions. Compared with the conventional braced tubes with regularly spaced multiple perimeter columns on every side of the building, braced megatubes with corner megacolumns are more efficient in resisting lateral wind loads. Structural design of tall buildings is generally governed by lateral stiffness. Depending on the stiffness distribution, the level of efficiency between different structural systems can vary substantially. This paper studies optimal structural design of braced megatubes in comparison with that of conventional braced tubes based on the optimal stiffness distribution for each. With the optimally designed structures, comparative efficiency between the systems is also evaluated. The heights of the comparatively studied braced tubes and braced megatubes range from 40 to 120 stories. These structures' height-to-width aspect ratios are between 4.3 and 13. While emphasis is placed on the optimal structural design and comparative structural efficiency of the braced tubes and braced megatubes, architectural design considerations are also discussed holistically.

Keywords: Tall Buildings, Structural Design, Lateral Stiffness, Stiffness-Based Design, Braced Tubes, Braced Megatubes, Premium for Height.

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1. Introduction

1.1. Early tall building structural systems

When only structural performance is considered for tall buildings, solid tube type structures can be considered as a very good solution. However, solid tubes with no fenestrations would be one of the most problematic architectural designs for occupants. In order to generate viable solutions both architecturally and structurally, various tube systems have been developed, such as framed, braced, bundled tubes, and more recently developed diagrids. Among these, braced tubes and diagrids with large perimeter diagonals are generally more efficient than framed and bundled tubes composed only of orthogonal members. This is because lateral loads in braced tubes and diagrids are primarily carried by axial actions due to the triangulation of the perimeter tube members including the large diagonals.

Between the optimally designed braced tubes with regularly spaced multiple perimeter columns on every side and diagrids with diagrid members placed at an optimal uniform angle, the braced tubes tend to be more efficient for very tall buildings with their height-to-width ratios larger than about eight (Moon, 2014). Regarding diagrid structures, their structural efficiency can further be increased by varying diagrid angles according to the structural logic (Baker et al., 2009; Moon, 2008). In the unbuilt 550-m tall diagrid Lotte Super Tower project by Skidmore, Owings & Merrill (SOM) for Seoul, the diagrid angles become steeper toward the base and shallower toward the top where the overturning moments and lateral shear forces govern the structural design, respectively (Besjak, et al., 2016; Boake, 2014). Braced tubes can also be designed more efficiently by placing the tube-composing perimeter columns more toward the corners, especially when a tall building with a square floor plan is considered (Rastorfer, 1985; Khan, 1972). Eventually, when all the perimeter columns are concentrated at the building corners, the structural efficiency can be maximized. When these adjustments for greater structural efficiency are made for both diagrids and braced tubes, the impact becomes greater for the braced tubes, making the system still more efficient than the diagrid system.

The first supertall braced tube structure is the 343-m tall 100-story John Hancock Center (now called 875 North Michigan Avenue) of 1969 in Chicago engineered by Fazlur Khan of SOM. With its structural steel use of only 29.7 psf (145 kg/m^2), this building is one of the most efficiently designed supertall steel structures (Ali, 2001; Schueller, 1990). Though Khan designed the John Hancock Center with the regularly spaced perimeter columns that

compose the braced tube with the diagonals, he already recognized at that time that that is not the most efficient structural configuration for supertall buildings.

"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. …… This then is the ultimate high-rise steel building." (Khan, 1972)

However, Khan did not design any tall building structure with his structural concept of "ultimate high-rise with four large corner columns." Only in recent years, this idea is finally applied to multiple supertall buildings, such as the 597-m tall 128-story Tianjin 117 (formerly Goldin

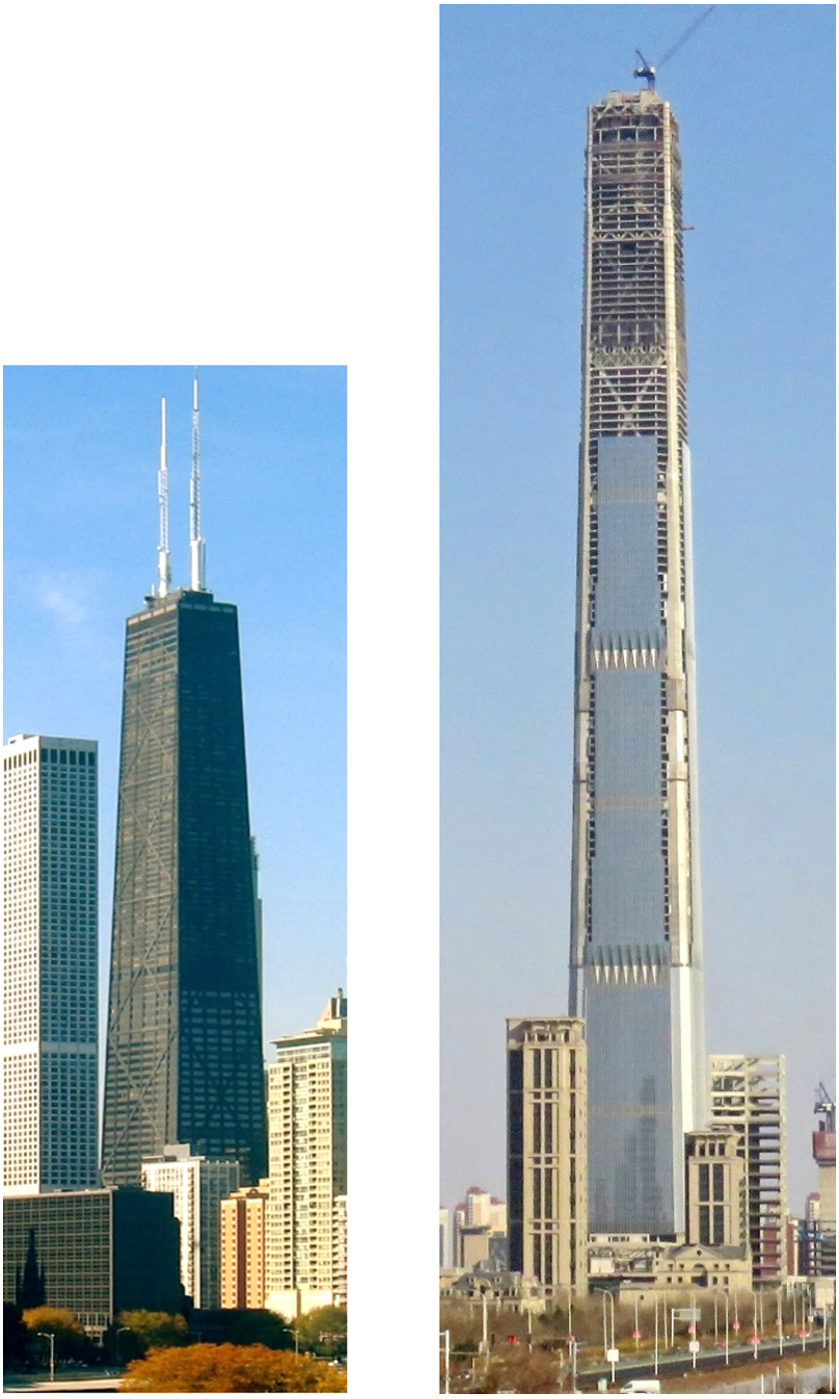


Figure 1. Examples of the braced tube with regularly spaced multiple columns on every side, 875 North Michigan Avenue (formerly John Hancock Center) in Chicago, and braced megatube with corner megacolumns, Tianjin 117 (formerly Goldin Finance 117) in Tianjin (Source: Wikipedia, photos taken by Jeremy Atherton and N509FZ, respectively).

Finance 117) under construction in Tianjin (Ho, 2017) and the unbuilt 569-m tall 105-story Hyundai Global Business Center project for Seoul (Moon and Kim, 2019). In this paper, these braced tube structures with corner megacolumns are called 'braced megatubes' while those with regularly spaced multiple perimeter columns on every side of the building, such as the John Hancock Center, are simply called 'braced tubes.' (Figure 1)

Structural design of tall buildings is governed by lateral stiffness in general. Though both braced tubes and braced megatubes are efficient structural systems for tall buildings, depending on the stiffness distribution, the level of efficiency can still vary substantially. While many studies have been performed on the conventional braced tubes that began to be used from late 1960s, investigations on more recently employed braced megatubes are limited. This paper studies the optimal structural design of the braced megatubes in comparison with that of the conventional braced tubes based on the optimal stiffness distribution for each. With the optimally designed structures, comparative efficiency between the systems is also evaluated. While emphasis is placed on optimal structural design and comparative structural efficiency, other important design issues such as architectural design considerations are also discussed holistically.

2. Stiffness-Based Design

Figure 2 presents a 100-story braced tube structure and its 10-story module subjected to lateral shear forces and overturning moments due to wind loads. The figure also shows the axial forces of the perimeter columns and diagonals that compose the braced tube. Through these axial actions of the columns primarily on the façade planes perpendicular to winds (flange planes) and bracings on the planes parallel to winds (web planes), overturning moments and lateral shear forces are carried, respectively. Participation of the perimeter columns on the web planes in carrying overturning moments is relatively small.

As the load-carrying mechanism is primarily by axial actions, the final step of the structural design includes determining member sizes of the columns and bracings in terms of their cross-sectional area. Based on the stiffness-based design methodology developed by Moon (2010),

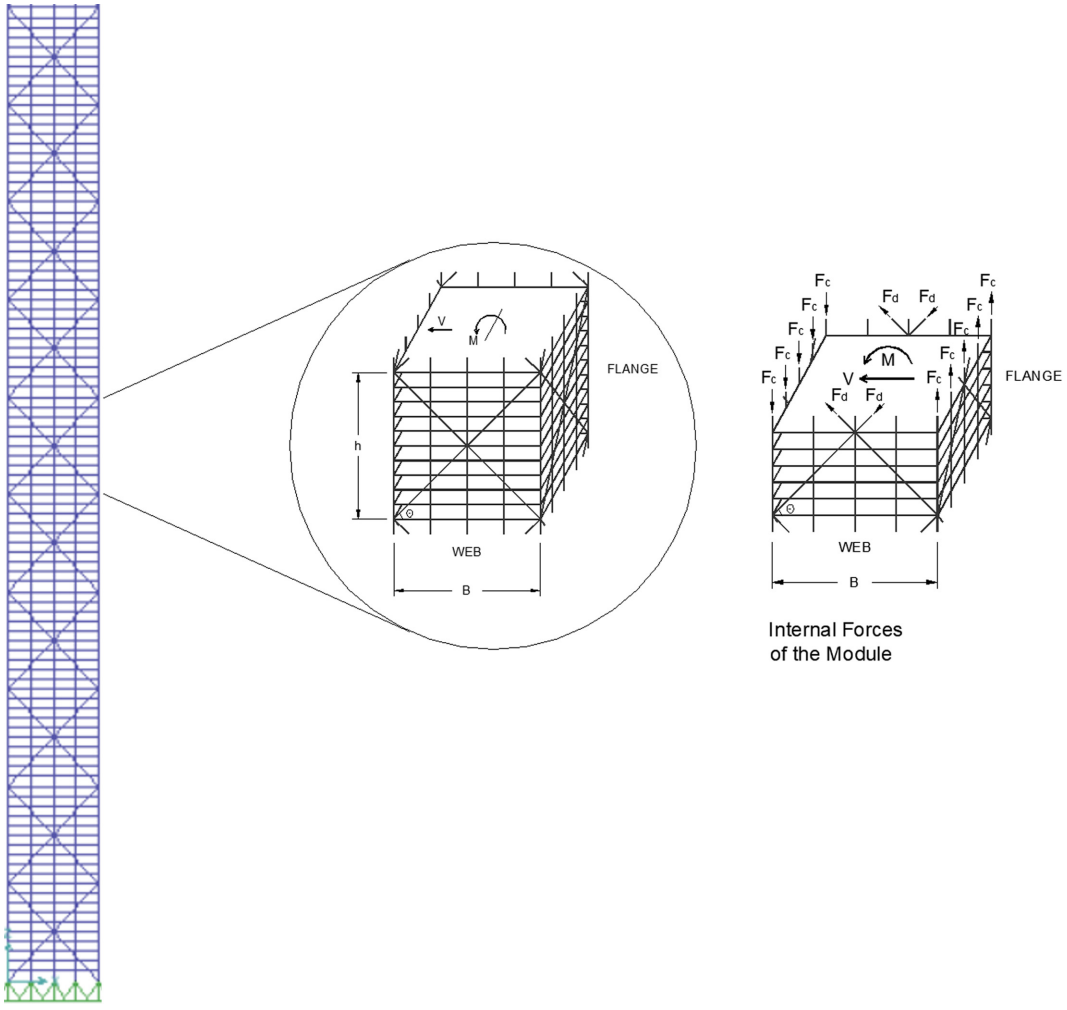


Figure 2. 100-story braced tube, its 10-story module and load-carrying mechanism by axial actions.

which is briefly reviewed as a basis for the expanded study presented in this paper, the cross-sectional areas of the perimeter columns and diagonals of the braced tube can be determined with Equations (1) and (2) respectively. These equations can be customized for design variations including braced megatubes with corner megacolumns. For instance, $n_{c,w}$ value, which is the contribution of the web plane columns to bending rigidity in Equation (1), becomes close to zero for the braced megatubes with only corner megacolumns. As will be presented in the following section, there are much smaller gravity columns between the corner megacolumns in the braced megatubes. However, their contribution to bending rigidity is negligible compared to that of the corner megacolumns.

$$A_c = 2M / (N_{c,f} + n_{c,w}) B^2 E_s k^* \quad (1)$$

$$A_d = V / 4E_s \cos^2\theta \sin\theta r^* \quad (2)$$

A_c : Cross-sectional area of each column of braced tube or braced megatube
A_d : Cross-sectional area of each diagonal of braced tube or braced megatube
B : Building width in the direction of lateral wind loads
θ : Angle of diagonals measured from horizontal
M : Overturning moment due to wind loads
V : Lateral shear force due to wind loads
$N_{c,f}$: Number of columns on each flange plane perpendicular to winds
$n_{c,w}$: Contribution of columns on web planes parallel to winds for bending rigidity
k^* : Desired curvature of braced tube or braced megatube
r^* : Desired transverse shear strain of braced tube or braced megatube
E_s : Modulus of elasticity of structural steel for tube-composing columns and bracings

Considering uniform shear and bending deformation for optimal design of a vertical cantilever beam representing a tall building structure (Connor, 2003), the maximum displacement at the top, *d (L)*, can be expressed by Equation (3). L is the height of the tall building.

$$\delta(L) = r^* L + k^* L^2 / 2 \quad (3)$$

For the most efficient structural design of tall buildings, it is critical to determine the optimal lateral stiffness distribution between shear and bending. Based on Equation (3), which is composed of the contributions of shear and bending deformations, the ratio of the maximum lateral displacement at the top due to bending to shear can be expressed as a dimensionless factor 's' as shown in Equation (4).

$$s = Lk^* / 2r^* \quad (4)$$

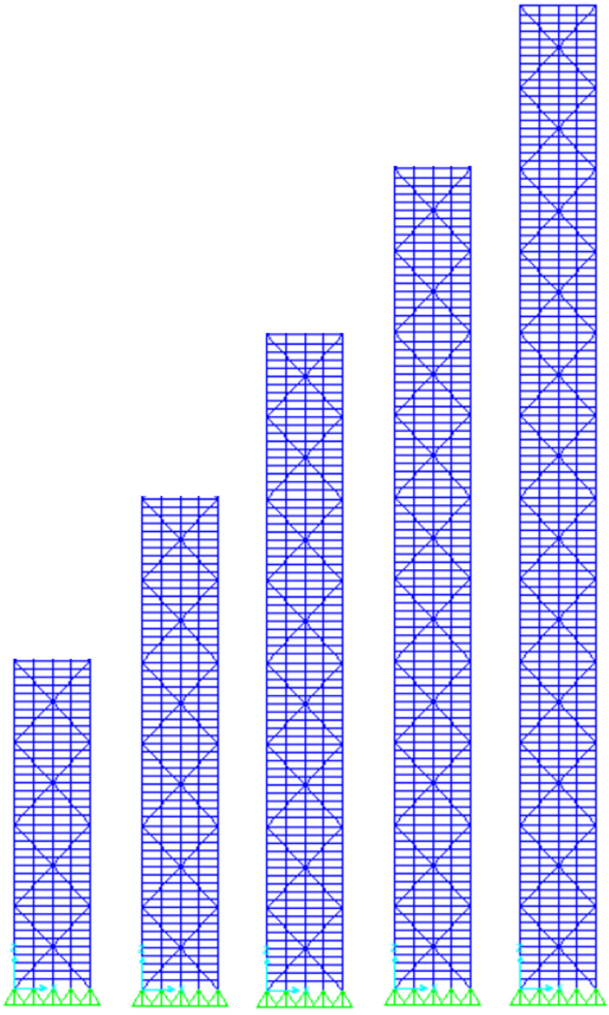


Figure 3. 40, 60, 80, 100 and 120-story braced tubes.

The maximum displacement of a tall building at the top is typically expressed as L/a, in which a value is usually between about 400 and 800 in many cases. The choice of a value is an important design decision and related to the function of the building in general. For example, residential towers that require greater occupant comfort use larger a values than office towers to limit their displacements. Then, the desired shear strain and curvature can be expressed in terms of s, a and L as shown in Equations (5) and (6).

$$r^* = 1 / (s + 1)\alpha \quad (5)$$

$$k^* = 2s / L(s + 1)\alpha \quad (6)$$

Various 's' values are tested for braced tubes and braced megatubes of different heights to identify optimal 's' values for each system of different heights. As the height of the building is increased, its height-to-width aspect ratio is also increased as the width of the structure is maintained identical throughout the study in this paper.

3. Comparative Optimal Stiffness Distribution

The design methodology presented in the preceding section is applied to 40, 60, 80, 100 and 120-story braced tube structures, with height-to-width aspect ratios ranging from 4.3 to 13 (Figure 3). The buildings have a square shape floor plan of 36 m × 36 m. The central cores are designed to carry only gravity loads, while the perimeter tube structures are designed to carry both lateral and gravity loads. The typical story height is 3.9 m in all cases. The module height of the braced tubes based on the diagonals placed at an angle of 47 degrees is 10 stories, and perimeter columns are placed at every 9 m.

The stiffness-based design methodology is also applied to the braced megatubes of the same heights and aspect ratios. Four corner megacolumns are used to form the braced megatubes. Between the corner megacolumns, much smaller gravity columns are placed at every 9 m since the 36-m spacing between the megacolumns would be too wide to span economically otherwise in the braced megatubes. 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 120-story braced tube and braced megatube structures are comparatively shown in Figure 4 in which member thicknesses are also expressed. Core structures that are designed to carry only gravity loads exist but are omitted from the view for clarity.

All structures are assumed to be in Chicago. Structural design is performed with the code-defined wind loads to meet the maximum lateral displacement requirement of *L/500* for all braced tubes and braced megatubes of various heights. Structural steel is used for the design of the braced tubes as well as braced megatubes. Steel is commonly used for braced tubes as are the cases with the John Hancock Center in Chicago and the First International Building in Dallas (Kowalczyk, 1995). For the braced megatubes, structural steel is also used in this study for direct comparison with the braced tubes. In today's real world projects, however, steel and concrete composite structures are also commonly used for the structural design of the braced megatubes as are the case with the Tianjin 117 in Tianjin and the unbuilt Hyundai Global Business Center project for Seoul.

Table 1 shows design summary in terms of the required amount of structural steel for the braced tubes of various heights ranging from 40 to 120 stories with 's' values

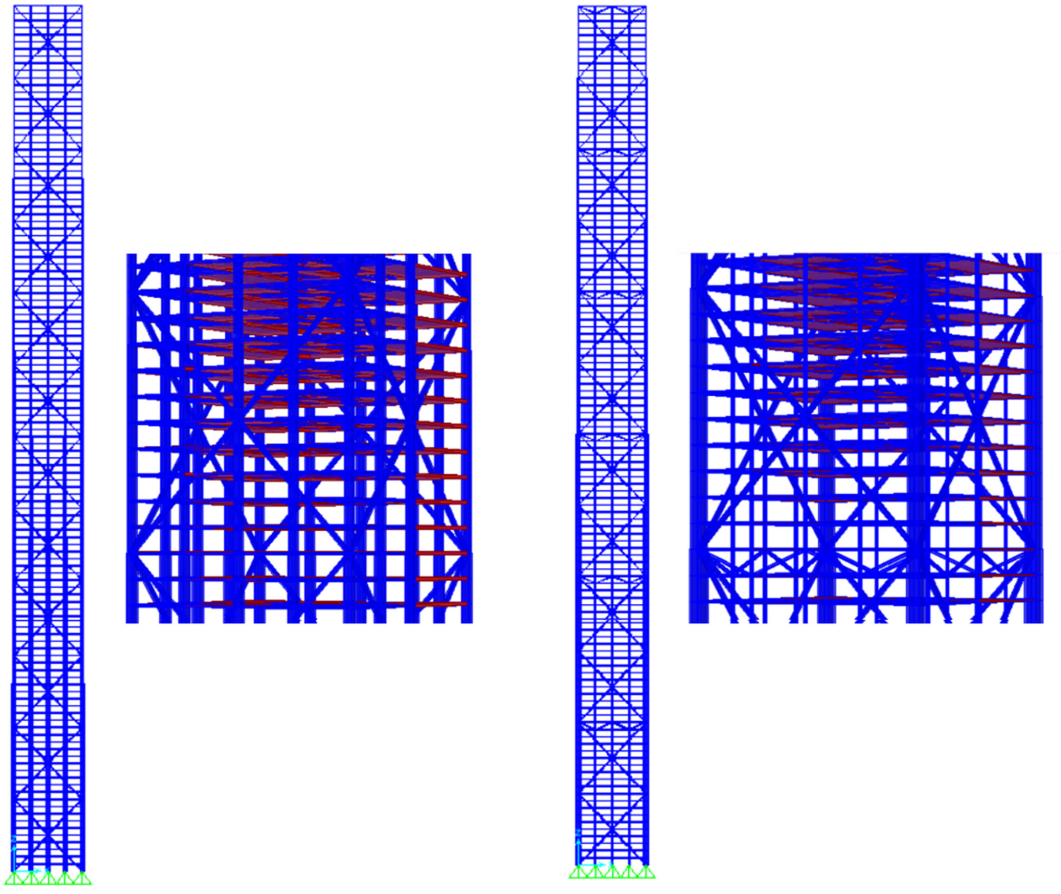


Figure 4. Elevation and partial three-dimensional views of the braced tube (left) and braced megatube (right) structures (core structures omitted from the view for clarity).

Table 1. Required steel for 40, 60, 80, 100, and 120-story braced tube structures with various 's' values ranging from 0.5 to 6 (optimal cases in bold fonts)

s	40-Story Braced Tube			60-Story Braced Tube			80-Story Braced Tube			100-Story Braced Tube			120-Story Braced Tube		
	Steel (ton)			Steel (ton)			Steel (ton)			Steel (ton)			Steel (ton)		
	Col	Dia	Total	Col	Dia	Total	Col	Dia	Total	Col	Dia	Total	Col	Dia	Total
0.5	1,085	223	1,308	5,987	560	6,547	20,208	1,075	21,283	51,393	1,762	53,155	108,580	2,596	111,176
1	723	297	1,021	3,992	746	4,738	13,472	1,434	14,905	34,262	2,349	36,611	72,386	3,461	75,848
1.5	603	372	974	3,326	933	4,259	11,227	1,792	13,018	28,551	2,937	31,488	60,322	4,327	64,649
2	542	446	989	2,994	1,120	4,113	10,104	2,150	12,254	25,696	3,524	29,220	54,290	5,192	59,482
2.5	506	520	1,027	2,794	1,306	4,100	9,430	2,509	11,939	23,983	4,111	28,095	50,670	6,057	56,728
3	482	595	1,077	2,661	1,493	4,154	8,981	2,867	11,848	22,841	4,699	27,540	48,258	6,922	55,180
3.5	465	669	1,134	2,566	1,679	4,245	8,660	3,225	11,886	22,025	5,286	27,311	46,534	7,788	54,322
4	452	743	1,195	2,495	1,866	4,361	8,420	3,584	12,004	21,414	5,873	27,287	45,242	8,653	53,895
4.5	442	818	1,260	2,439	2,052	4,492	8,233	3,942	12,175	20,938	6,461	27,398	44,236	9,518	53,755
5	434	892	1,326	2,395	2,239	4,634	8,083	4,301	12,384	20,557	7,048	27,605	43,432	10,384	53,816
5.5	427	966	1,394	2,359	2,426	4,784	7,961	4,659	12,620	20,246	7,635	27,881	42,774	11,249	54,023
6	422	1,041	1,463	2,329	2,612	4,941	7,859	5,017	12,876	19,986	8,223	28,209	42,225	12,114	54,340

Table 2. Required steel for 40, 60, 80, 100, and 120-story braced megatube structures with various 's' values ranging from 0.5 to 6 (optimal cases in bold fonts)

s	40-Story Megatube			60-Story Megatube			80-Story Megatube			100-Story Megatube			120-Story Megatube		
	Steel (ton)			Steel (ton)			Steel (ton)			Steel (ton)			Steel (ton)		
	Col	Dia	Total	Col	Dia	Total	Col	Dia	Total	Col	Dia	Total	Col	Dia	Total
0.5	746	223	969	4,116	560	4,676	13,893	1,075	14,968	35,332	1,762	37,094	74,648	2,596	77,244
1	497	297	795	2,744	746	3,491	9,262	1,434	10,695	23,555	2,349	25,904	49,766	3,461	53,227
1.5	414	372	786	2,287	933	3,220	7,718	1,792	9,510	19,629	2,937	22,566	41,471	4,327	45,798
2	373	446	819	2,058	1,120	3,178	6,946	2,150	9,097	17,666	3,524	21,190	37,324	5,192	42,516
2.5	348	520	868	1,921	1,306	3,227	6,483	2,509	8,992	16,488	4,111	20,600	34,836	6,057	40,893
3	331	595	926	1,830	1,493	3,322	6,175	2,867	9,042	15,703	4,699	20,402	33,177	6,922	40,100
3.5	320	669	989	1,764	1,679	3,443	5,954	3,225	9,179	15,142	5,286	20,428	31,992	7,788	39,780
4	311	743	1,054	1,715	1,866	3,581	5,789	3,584	9,373	14,721	5,873	20,594	31,104	8,653	39,757
4.5	304	818	1,122	1,677	2,052	3,729	5,660	3,942	9,602	14,395	6,461	20,855	30,412	9,518	39,931
5	298	892	1,190	1,647	2,239	3,886	5,557	4,301	9,858	14,133	7,048	21,181	29,859	10,384	40,243
5.5	294	966	1,260	1,622	2,426	4,047	5,473	4,659	10,132	13,919	7,635	21,554	29,407	11,249	40,656
6	290	1,041	1,331	1,601	2,612	4,213	5,403	5,017	10,420	13,740	8,223	21,963	29,030	12,114	41,144

from 0.5 to 6 with its increment interval of 0.5. As can be observed, the optimal 's' value is increased as the building height and consequently its height-to-width aspect ratio is also increased. While the optimal 's' value of the 40-story braced tube structure is 1.5, that of the 120-story braced tube is 4.5. This means that the 40-story braced tube should be designed to have 1.5 times larger bending-induced displacement than the shear-induced displacement at the top, while the 120-story braced tube should be designed to have 4.5 times larger bending-induced displacement than the shear-induced displacement at the top, to meet the target displacement criteria most efficiently.

Table 2 shows design summary of the braced megatubes of various heights ranging from 40 to 120 stories with 's' values from 0.5 to 6. As was the case in the braced tubes, the optimal 's' value is also increased as the building height is increased. However, the overall optimal 's' values are slightly smaller in the braced megatubes than in the braced tubes. The optimal 's' values for the 40, 60, 80, 100, and 120-story braced tubes are 1.5, 2.5, 3, 4 and 4.5, while those for the braced megatubes are 1.5, 2, 2.5, 3 and 4. This is because that 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.

4. Premium for Height

The amount of required structural materials is increased exponentially as a building becomes taller. Table 3 and Figure 5 summarize the required amount of structural steel for the optimally designed braced tubes and braced megatubes of 40, 60, 80, 100 and 120 stories to meet the same target displacement of *L/500* based on the stiffness-based design methodology presented in this paper. The required structural steel amounts are increased drastically for taller structures, and that is due to the "premium for height." Employing a more efficient structural system can reduce the premium for height. As the braced megatube is more efficient than the braced tube, its structural steel use is substantially reduced. For taller structures, this reduction is accelerated.

For the braced tube type structures, the premium for height is caused primarily by the required structural materials for perimeter columns that compose the tube system. Figure 6 shows the required amount of structural steel for the perimeter columns along the heights of the braced tubes and braced megatubes of 40, 60, 80, 100 and 120 stories. The exponential increase of the column sizes toward the base of the structure can be observed in all cases as the overturning moments are increased similarly.

In terms of the premium for height, it is clear that the required column sizes of the same story heights are increased drastically for taller structures despite that higher optimal 's' values required for taller structures contribute to somewhat pulling down the exponential increase of column sizes for taller structures. Between the braced tubes and braced megatubes, the latter requires smaller amounts of structural steel for the tube-forming perimeter columns because the bending rigidity against the overturning moments provided by the perimeter columns of the same amount of structural steel is greater in the braced megatubes than in the braced tubes. This is because of the maximized structural depth by the corner megacolumns in the braced megatubes. Taller structures result in greater percentile reduction in steel use in the braced megatubes as also shown in Table 3.

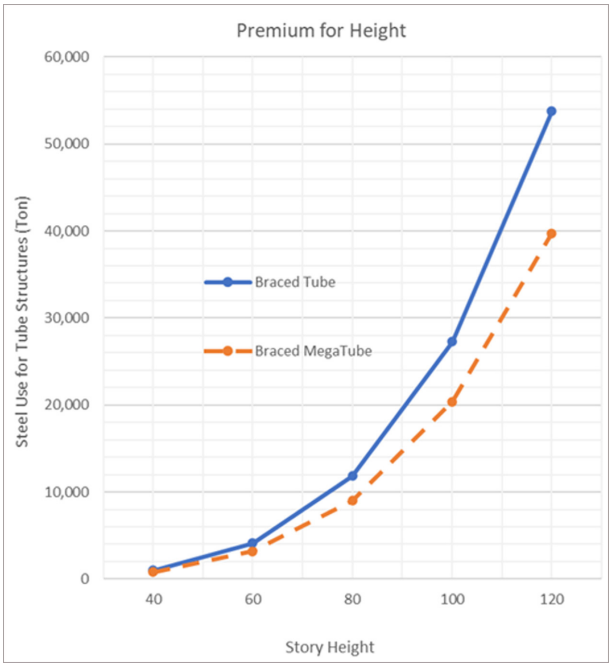


Figure 5. Premium for heights for braced tubes and braced megatubes of 40, 60, 80, 100 and 120 stories with their height-to-width aspect ratios ranging from 4.3 to 13.

Contribution of the bracings to the premium for height is relatively small compared to that of the columns. Figure 7 shows the required amount of structural steel for the perimeter diagonal bracings of the braced tubes and braced megatubes of 40, 60, 80, 100 and 120 stories. Unlike the sizes of the columns that increase exponentially toward the base, the bracing sizes increase more or less linearly. Indeed, the incremental rate is slightly decreased toward the base because wind loads are not uniform throughout the height but reduced toward the base.

In terms of the premium for height, the required amount of structural steel for the bracings increases more than proportionally for taller buildings. One factor that makes this tendency is related to lateral wind loads a tall building is subjected to. Lateral wind loads are increased toward the top of the building at a decreasing rate of increase. Therefore, taller structures are subjected to lateral shear forces somewhat larger than proportional to the height increase. Another factor that makes the bracings

Table 3. Required structural steel for the optimally designed 40, 60, 80, 100, and 120-story braced tube and braced megatube structures

Story	Height/Width	Braced Tube		Braced MegaTube		Percentile
Height	Aspect Ratio	s	Steel (ton)	s	Steel (ton)	Difference
40	4.3	1.5	974	1.5	786	–19.3%
60	6.5	2.5	4,100	2	3,178	–22.5%
80	8.7	3	11,848	2.5	8,992	–24.1%
100	10.8	4	27,287	3	20,402	–25.2%
120	13.0	4.5	53,755	4	39,757	–26.0%

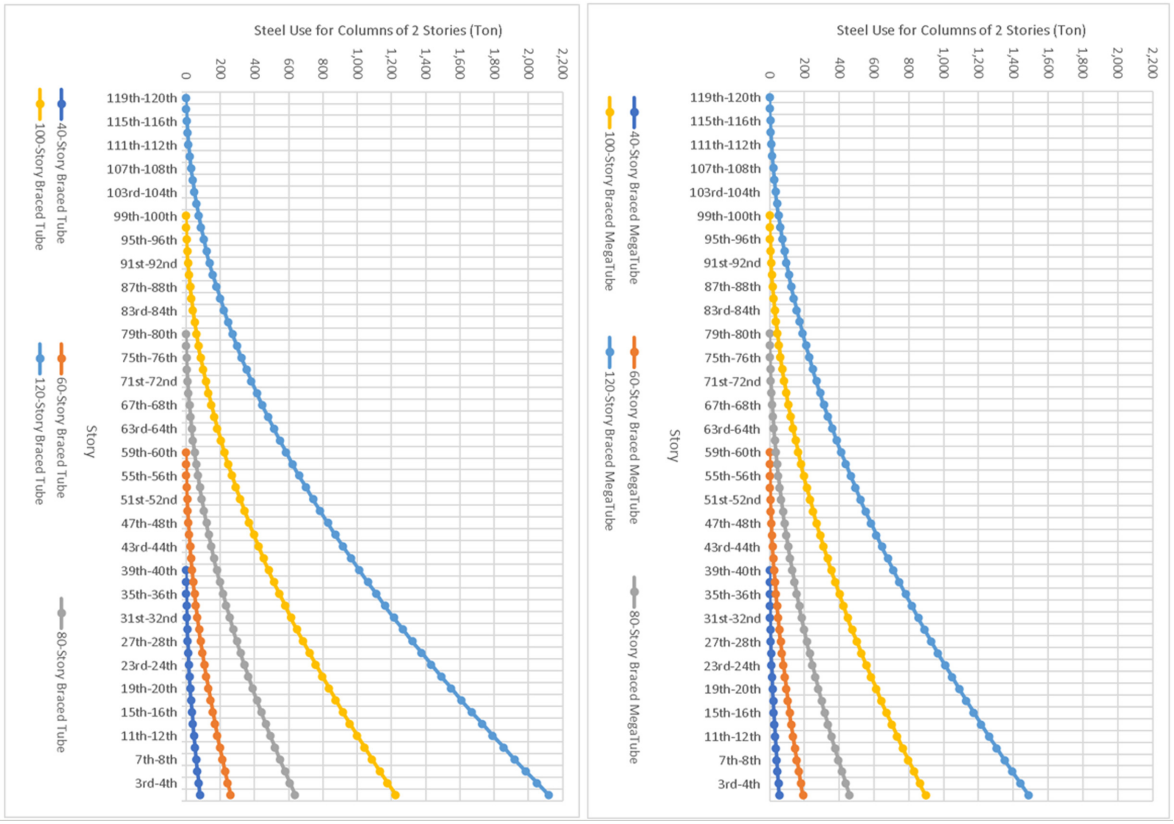


Figure 6. Required amount of structural steel for the perimeter columns along the heights of the braced tubes (left) and braced megatubes (right) of 40, 60, 80, 100 and 120 stories.

contribute to the premium for height is related to the higher optimal 's' values required for taller structures. As the 's' value increases, the required bracing sizes increase proportionally. Because higher optimal 's' values are required for taller structures due to their behavioral characteristics, this makes the bracing sizes for taller buildings larger than proportional to the height increase.

Unlike the perimeter columns, the configurations of the perimeter diagonal bracings are identical in both braced tube and braced megatube structures. Therefore, the required bracing sizes should in fact be identical for the same height structures if the same 's' value is used for both structures. However, the optimal 's' values are typically smaller for the braced megatubes as explained earlier. Therefore, the required amount of steel for bracings is also smaller in the braced megatubes in general as can be observed in Figure 7.

It is also noted that as various 's' values are tested to find the optimal values with an increment interval of 0.5, the finalized optimal 's' value differences vary between 0.5 and 1 for the structures of different heights. That explains the different incremental tendency in steel use for the bracings of the braced tubes and braced megatubes as shown in Figure 7. The optimal 's' values for every case were presented in Table 3.

Figure 8 shows how the perimeter-tube-composing columns and bracings contribute to the premium for height differently in the braced tubes and braced megatubes of 40, 60, 80, 100 and 120 stories with their height-to-width aspect ratios ranging from 4.3 to 13. It clearly shows that the contribution of the columns is dominant between the columns and bracings. Column sizes are drastically increased for taller structures. Though the bracing sizes are also increased greater than proportional to the height increase for taller structures, its incremental rate is much more moderate when compared to that of the column sizes.

Consequently, as a building becomes taller, the required amount of structural material for the tube-composing columns becomes much greater than that for the bracings in the optimally designed braced tubes and braced megatubes. Table 4 shows the required amount of steel in percentage for the columns and bracings of the optimally designed braced tubes and braced megatubes as their heights and height-to-width aspect ratios are increased.

Figure 9 shows the comparative required steel in percentage for the perimeter-tube-composing columns and bracings of the optimally designed braced megatubes of various heights. For the 40-story braced megatube structure with its height-to-width aspect ratio of 4.3, the required amounts of steel for the corner megacolumns and bracings are similar. However, in the 120-story braced megatube structure with its aspect ratio of 13, the required amount

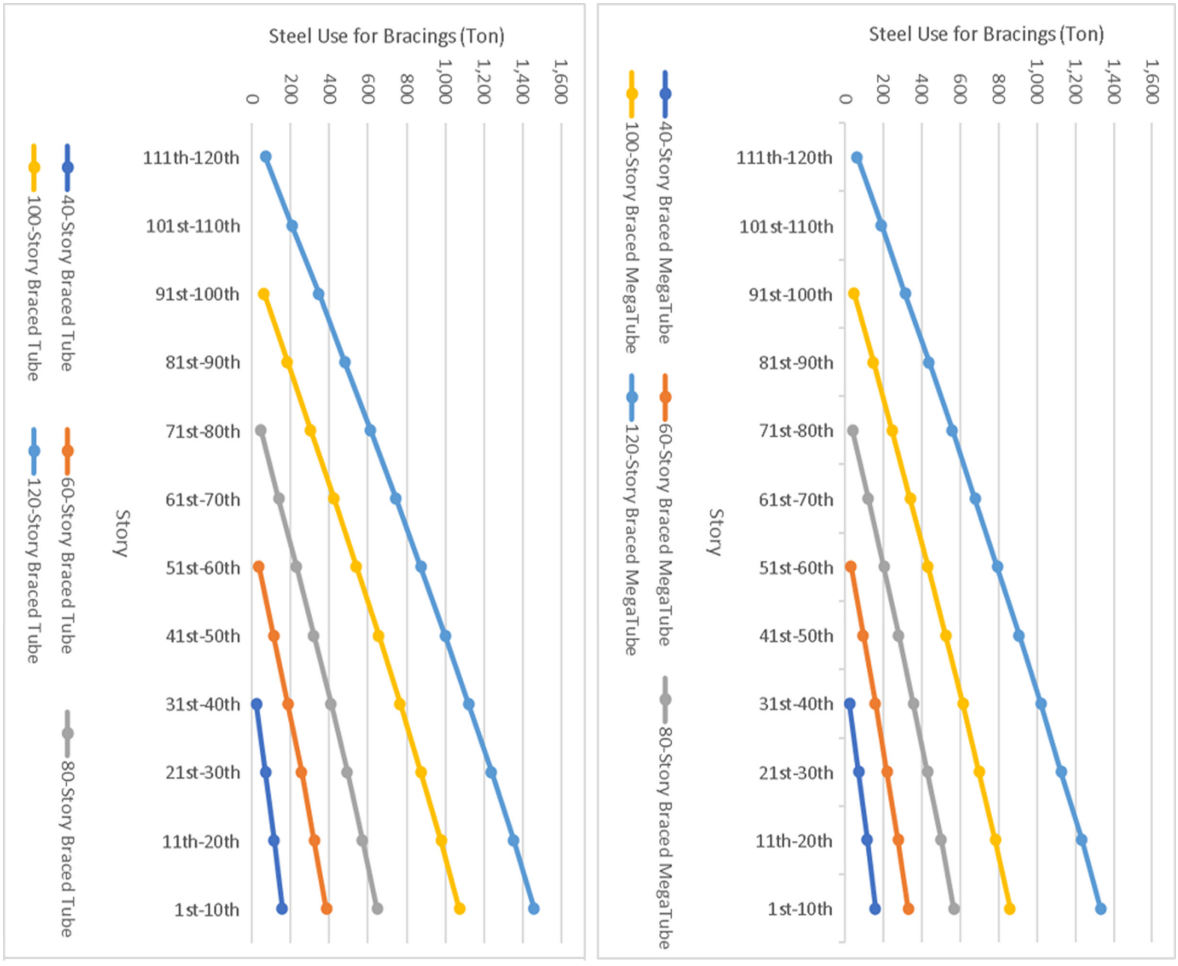


Figure 7. Required amount of structural steel for the perimeter diagonal bracings along the heights of the braced tubes (left) and braced megatubes (right) of 40, 60, 80, 100 and 120 stories.

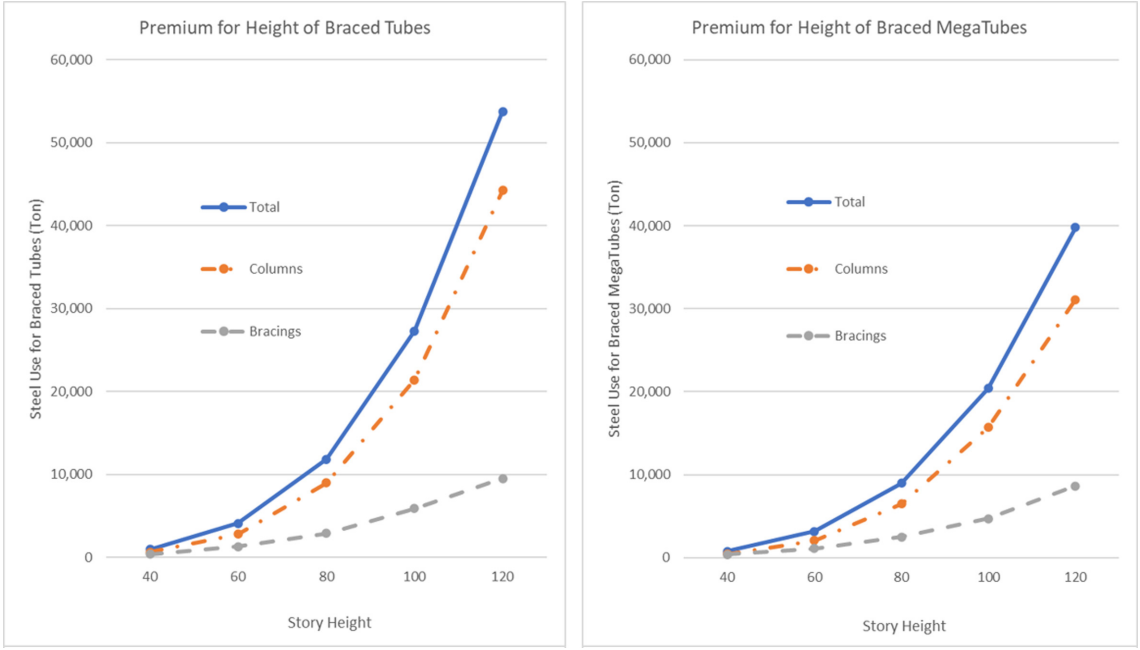


Figure 8. Contribution of the perimeter-tube-composing columns and bracings for the premium for height in braced tubes and braced megatubes of 40, 60, 80, 100 and 120 stories.

Table 4. Required steel in percentage for perimeter tube-composing columns and bracings of the optimally design braced tubes and braced megatubes

Story	Height/Width	Required Steel for Braced Tubes		Required Steel for Braced MegaTubes	
Height	Aspect Ratio	Columns	Bracings	Columns	Bracings
40	4.3	62%	38%	53%	47%
60	6.5	68%	32%	65%	35%
80	8.7	76%	24%	72%	28%
100	10.8	78%	22%	77%	23%
120	13.0	82%	18%	78%	22%

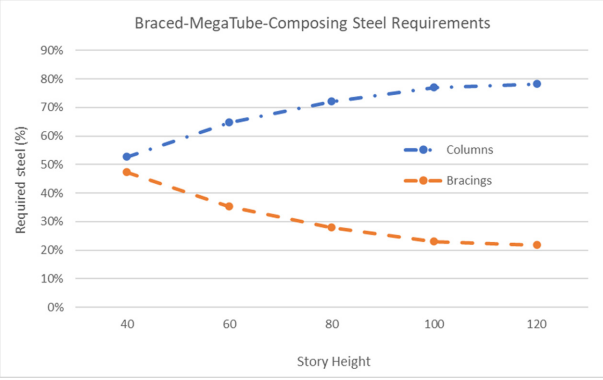


Figure 9. Comparative required steel in percentage for the perimeter-tube-composing columns and bracings of the optimally designed braced megatubes of various heights.

of steel for the corner megacolumns is almost five times larger than that for the bracings.

5. Integrative Design

In the braced tube type structures, how to arrange the tube-composing members has a great impact on their structural efficiency. Considering the large amount of required structural materials that are increased exponentially for taller buildings, the contribution of employing more efficient structural systems with their more efficient geometric configurations is significant for sustainable engineering that uses smaller amounts of structural materials coming from our limited natural resources.

The most efficient structural configuration, however, does not always produce the most desired architectural design. As studied earlier in this paper, braced megatubes with corner megacolumns generate one of the most efficient structural systems for tall buildings. However, corner megacolumns are not always welcomed architecturally. Indeed, column-free open corners are often much coveted architecturally as a condition to provide premium spaces. A feasible design alternative to not diminish too much the structural efficiency of the braced megatubes and provide column-free open corners is using split corner megacolumns. Instead of placing a gigantic megacolumn at each corner, two smaller megacolumns can be placed somewhat away



Figure 10. CITIC Tower in Beijing during construction. (Source: Wikipedia, photo taken by Bairuilong)

from the very corner. Then, the column-free corners can be cantilevered from between the split megacolumns. As the distance between the split megacolumns is increased, the structural efficiency is decreased, while larger column-free corner openings are produced, and vice versa. Therefore, careful studies are required to meet the structural and architectural design requirements holistically.

The 528-m tall CITIC Tower of 2018 in Beijing is a good example employing split megacolumns at each corner of the braced megatube (Figure 10). This building uses a gigantic single megacolumn at each corner at lower floors where greater lateral stiffness is required, while split corner megacolumns are used for typical floors to better integrate them with architectural design without diminishing structural efficiency too much.

The optimal stiffness distribution for a selected system and its configuration is also very important for more

efficient and consequently more sustainable structural engineering for tall buildings. Depending on the system and its geometric configuration, optimal lateral stiffness distribution varies. This variation results in different proportioning between the column and bracing sizes. While the sizes of the columns and bracings certainly influence architectural design, their impact is usually not as substantial as that of the system selection and selected system's overall geometric configuration.

6. Conclusions

Structural efficiency of using large diagonal bracings in combination with orthogonal frames was recognized from the early days of tall buildings in the late 19th century. The efficiency of this structural configuration became significantly larger when the braced tube structure was developed in the 1960s. With the braced megatubes, the structural efficiency can finally be maximized. Though the braced megatubes were also conceived at the time of the traditional braced tube development, their application to real world projects can only be found in recent supertall buildings.

Once a certain structural system is selected for the design of a tall building, it is important to study its optimal stiffness distribution for the most efficient structural design. This paper presented optimal structural design of braced megatubes in comparison with the conventional braced tubes based on a stiffness-based design methodology. Both systems should be designed to produce greater bending displacement than shear displacement for greater efficiency. Bending to shear displacement ratios should become larger as the structures become taller and consequently their height-to-width aspect ratios become larger. Between the braced tube and braced megatube, the braced megatube should be designed to produce smaller bending to shear displacement ratio than the braced tube of the same height and aspect ratio for the optimal design.

While selecting a certain structural system for a tall building is not determined based only on structural efficiency, it is very important to select an efficient system and optimize its design to save structural materials that come from our limited natural resources. As tall buildings become ever taller, this becomes even more important because taller buildings require exponentially larger amounts of structural materials due to the premium for height. Nonetheless, since the most efficient structural design may not always best satisfy architectural and other design requirements, the design should be performed integratively to create more livable and sustainable built environments.

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