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Modifying Tall Building Form To Reduce the Along-Wind Effect


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In order to reduce undesirable wind effects and structural responses in tall buildings, there are two main solutions: architectural and structural. Architects can mitigate the wind effect on tall buildings by designing the form aerodynamically, or at least by using tapering and setbacks. Structural engineers can reduce wind effects by choosing and designing efficient structural systems, such as the tube and diagrid systems. This research introduces an alternate design method, by creating an innovative computational workbench to design efficient tall buildings to withstand and adapt to the along-wind effect. An architectural parametric design procedure in AutoLisp (AutoCAD) generates the models, and is connected with a Computational Fluid Dynamics (CFD) program (ANSYS) and a structural analysis program (SAP2000).

Introduction

One of the most influential parameters in the structural design of tall buildings, in addition to gravity loads, is the lateral load resulting from wind, and to some extent, earthquakes. Tall buildings have to be designed for a larger base shear from wind forces than from seismic forces; however, ductile detailing is used when needed to account for seismic demands. The wind effect occurs primarily in two main modes of action: across-wind and along-wind. For a rectangular building, the two faces along the mean wind direction are considered the along-wind direction and the two perpendicular faces to the mean flow are considered across-wind (Alaghmandan & Elnimeiri 2013).

The architectural strategies (such as macro- and micro-aerodynamic modifications) are basically considered as precautionary ways to reduce the impact of wind, and subsequently to mitigate the weight of the structure and the cost of the construction. Micro-level modifications tend to involve corner cuts and rounding; macro modifications are geometric and at the whole-building scale, such as tapering and setbacks. The shape and the geometry of tall buildings and aerodynamic modifications can reduce the wind effect (Irwin 2009; Ilgin & Gunel 2007; Irwin, Kilpatrick & Frisque 2008; Amin & Ahujab 2010; Kareem, Kijewski & Tamura 1999; Sevalia, Desai & Vasanwala 2012).

Determining the effect of the type of structural system, based on the form and the shape of tall buildings, is another main objective of this research. Regarding the architectural characteristic of tall buildings, lateral-load-based structural systems, such as tube and outrigger systems, can be designed to reduce the dynamic response of the structure of tall buildings, and consequently to reduce the weight of the structure (Ali & Moon 2007; Moon 2009, 2011).

This research, using architectural and structural strategies to reduce wind effect, introduces a new design method in the realm of tall buildings to achieve minimum structural weight. These kinds of considerations depend on the collaboration of architects and engineers through the design process.

To achieve more efficient buildings, it is necessary to design a common workbench of architectural, structural, and CFD programs

“Considering the estimated weight of the diagrid system with beams, this solution can be the most efficient system for models with less than three degrees of tapering.”

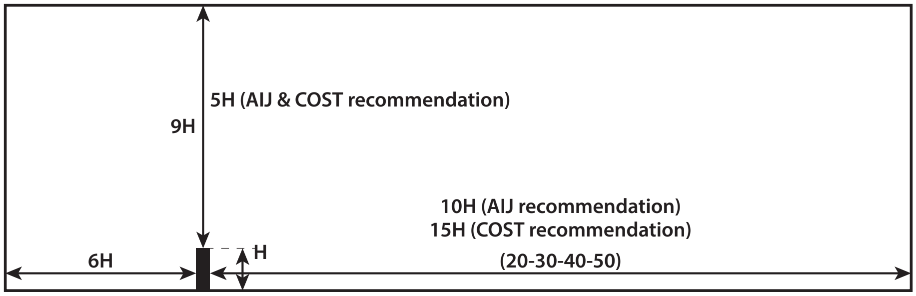

Figure 1. Determining the domain size.

to work together. This method facilitates a comprehensive integration of architectural, structural, and wind aspects to gain the most efficient geometry and form with the minimum wind impact and minimum structural weight, while still achieving the formal functional intents of the building. In this paper, the computing workbench and a test on a building with tapering modifications will be briefly illustrated.

Computational Process

In this proposed design method, there are three main steps to determine the final results and achievements. Based on the CFD results, the lateral force of wind on the windward and leeward sides of the parametric models is obtained for use in the structural analysis and design (Alaghmandan et al. 2014).

CFD simulation

The first step of CFD simulation is to determine the goals and identify the domain of the model. This includes creating a solid model to represent the domain and designing and creating the mesh. In the next step, the preprocessing and solver execution has to be run.

The AIJ (Architectural Institute of Japan) and COST (European Cooperation in Science and Technology) guidelines are used in implementing the ANSYS CFD program.

Determining boundary and meshing size

The models are simulated full-scale in a vertical section 64 meters wide and 360 meters tall. For the size of the computational domain, representing a single tall building model, the lateral and the top boundaries are set at a point least at least five times the height (5H) of the building, and the outflow boundary is set at least 10H and 15H behind the building. The buildings included in the computational domain should not exceed the recommended blockage ratio (3%), where H is the height of the target building (Tominaga et al. 2008; Franke et al. 2004). In this example, the goal is to find the optimal size of the downwind distance from the obstacle, so the basic model is simulated and checked with four sizes (see Figure 1).

For verifying the size, the force pressure is shown in Figure 2. This shows that after 30H, the differences among the results are negligible; thus, 30H is set for the downwind distance for this research. In general, the outflow boundary needs to be far enough from the building to achieve negligible influence by the target building on the wind pattern.

The mesh size before the obstacle divided into 720 segments, with a bias factor of 40. The mesh size after the obstacle is divided into 120 segments, with a ratio of six as the bias factor. For determining the optimal size of the meshing, the basic model is simulated with six different sizes of mesh. The effect of the meshing size on the obstacle and the force pressure is shown in Figure 3. Here it is shown that after 0.3 meters' meshing size, the differences among the results are negligible, so it is set for the basic meshing size in this research.

Based on the aforementioned illustrations, all of the model's iterations are linked in to the ANSYS meshing module for accuracy. The parameters of the ANSYS meshing procedure and its FLUENT CFD simulation must be carefully adjusted to yield enough results to be meaningful.

The main goal in testing gridding and meshing is certifying that the prediction result does not change significantly as the grid systems are changed. In this case, the meshing is good enough to do the final CFD simulation. It is also necessary to ensure that the aspect ratios of the grid shapes do not become excessive on regions adjacent to coarse grids or near the surfaces of the obstacle. It is also best to arrange the prismatic cells parallel to the walls or the ground surfaces for the unstructured grid system (Tominaga et al. 2008; Franke et al. 2004).

After determining the domain and meshing considerations and creating the name section for each wall of the model in the FLUENT procedure, the material properties are defined as fluid, solid, or mixture. Then, solver settings such as numerical schemes and convergence controls have to be set and computed. Basically, the discredited conservation equations are solved until convergence is achieved.

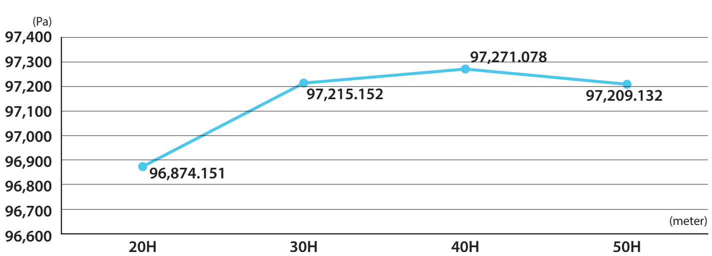

Figure 2. Total force report regarding different domain (outflow) sizes.

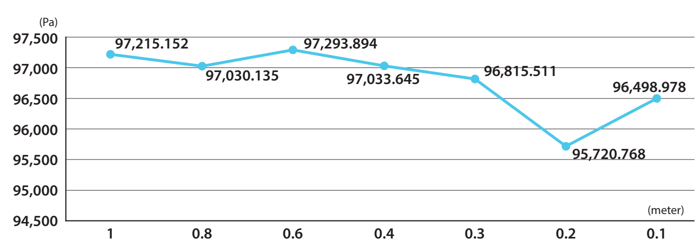

Figure 3. The total force report regarding meshing size.

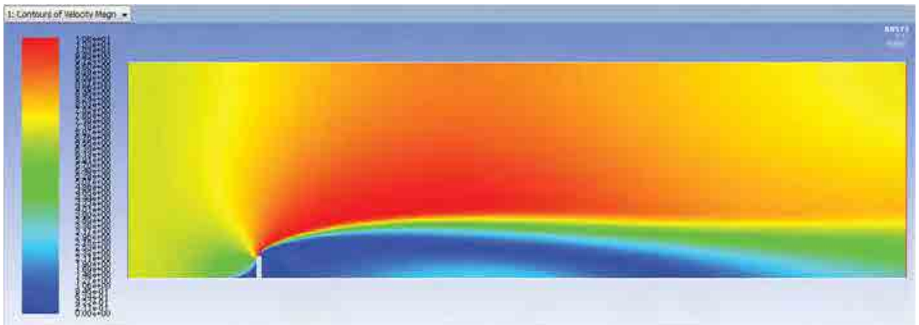

Figure 4. CFD simulation of the basic model in FLUENT (contour of velocity).

Figure 5. The variation of the angles of the tapering models.

One of the most important parameters of the FLUENT process set-up is defining the models of simulation. In researching this particular model, the RNG (Re-Normalization Group) method using a *k–ε* model with a standard wall function is set. Based on both aforementioned guidelines, the first-order upwind scheme is not appropriate for all transported quantities, since the spatial gradients of the quantities tend to become diffusive due to a large numerical viscosity; thus, the second-order scheme is chosen for the simulations. Figure 4 shows the visual contour of the wind velocity on the basic model. In this research, the mean wind speed for the CFD simulation is 25.2 km/h (7 m/s).

Parametric modeling

The second step is to design a model using the architectural parametric procedure in AutoLisp (AutoCAD). The 3D parametric models for the structural analysis and design program (SAP2000) used in the third step are generated with AutoLisp language, which sets the parameters of the models. The wind-load results from ANSYS are then saved in AutoLisp, which will be readable in SAP2000 (Alaghmandan et al. 2014).

In the parametric design process of this research, the parameters of the models are set based on the equal gross area of the buildings for all generations because it is necessary to have the same models based on the same architectural efficiency, which is dependent on the total gross area. The basic parametric model has a 64-square-meter plan and a 360-meter height, representing a 90-story office building. In this research, a tapering effect in two structural systems (frame tube and diagrid) is generated.

For this particular example, the tapering angle is between three and eight degrees. This variation does not mean all the models are acceptable architecturally, structurally, or functionally. Figure 5 shows 12 models as samples.

Structural analysis

In the design of tall buildings, structural designers "want to use the minimum material to resist a prescribed wind load without exceeding a deflection criterion, such as tip deflection" (Baker 1992). Hence, for designing an efficient structural system for a tall building with the least volume of material, it is useful to determine the deflection contribution of each member. A desired roof displacement can be met through an optimization process that reassigns groupings of members with different discrete shapes so that all groups have the same strain energy density or contribution to the displacement. As material is redistributed, a lighter structure is achieved. (Gilsanz & Carlson 1991)

This research uses nonlinear dynamic analysis with a the deflection limit of H/500 for the models, based on Chicago Building Code (CBC). The structural analysis and design part is based on AISC-ASD steel code requirements. The dead, live, and wind loads are the load patterns and cases for the models. The wind load is transferred as a user-defined table that comes from ANSYS results. The distance between the columns in the frame tube is four meters, and the width and height of the diagrid module is set as a floor height.

The simulation and computing processes, encompassing AutoCAD 13, ANSYS 14.5, and SAP2000 V16.1.1 have to run automatically under a coding script. Visual Basic (VB) is chosen to facilitate writing the code through a Microsoft Excel file interface. First, ANSYS is opened and the journal file is run to get the wind forces from FLUENT, which are then entered as the wind loads of the model. Then, AutoCAD is opened and the AutoLISP script is run to create a *.s2k* file containing all the information and parameters needed for SAP2000 to run analysis of the structural design. This yields results such as total base moment, total base shear, and the total weight of the structure (Alaghmandan et al. 2014).

The research methodology process, research framework, the main parts of the proposed methodology process, and the details of the research workflow actually performed are shown in Figure 6.

Study Results

CFD Results

Figures 7 and 8 show the wind pressure on the windward and leeward sides of 12 models representing different tapering effects. Increasing the tapering angle applies less pressure on the windward side, particularly close to the top of the models. As can be seen on the figures, the interesting point is that the pressure at the top of the windward face is negative in all the models; there is a suction effect on that part of the buildings.

The leeward diagrams of the models with -2, -1, 1, and 2 degrees of tapering demonstrate an unexpected effect. A minor adjustment to tapering angles can cause a more complex

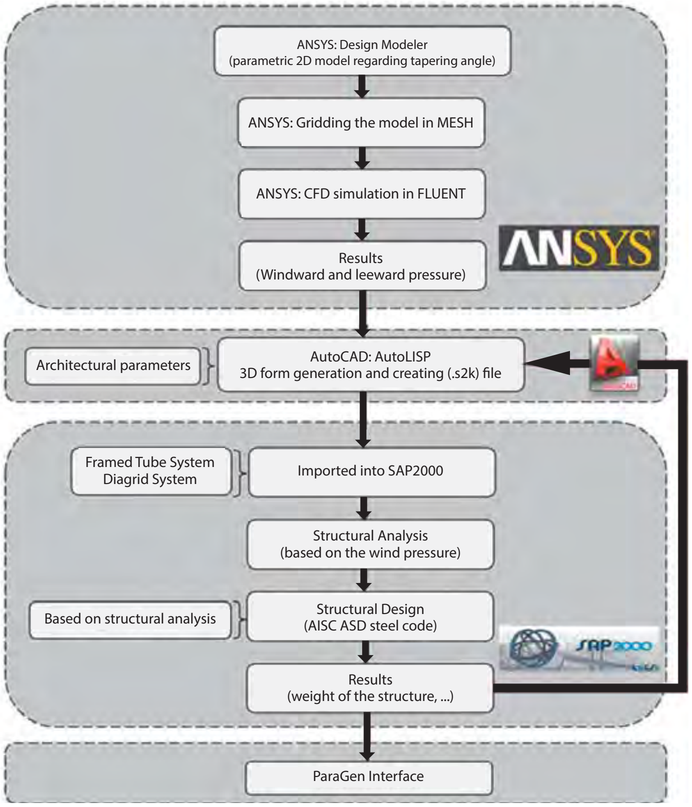

Figure 6. Detailed research workflow.

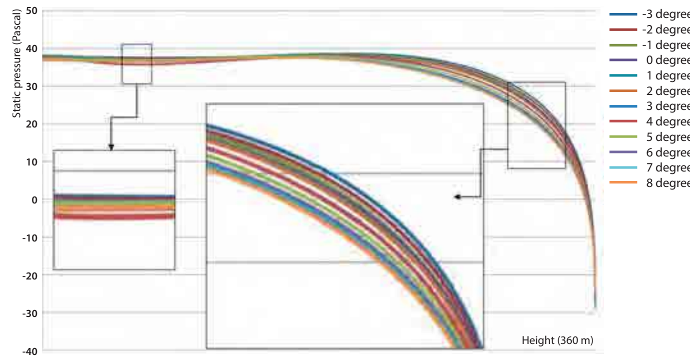

Figure 7. Windward static pressure diagram of 12 different angles of tapering.

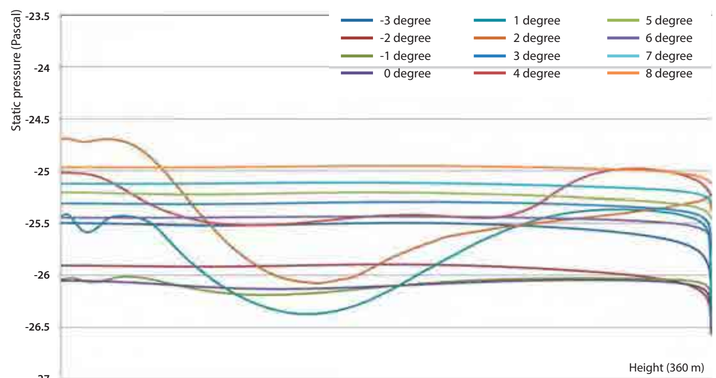

Figure 8. Leeward static pressure diagram of 12 different angles of tapering.

leeward effect on a building. Wider tapering angles of six to eight degrees have very straightforward and expected effects on the leeward building sides.

Structural results

The total base shear and base moment with tapering modifications are shown in Figures 9 and 10. By this consideration, the effect of changing the geometry to modulate along-wind effect on the structural factors (base shear, base moment) is determined.

Based on Figure 9, the norm of the trend of the total base shear forces is going to be decreased from -3 to 8 degrees of tapering; the lowest total base shear can be compensated by a higher tapering degree, regarding the along-wind effect. In this figure, there are some unexpected results far from the general trend. The reason(s) for this can be investigated in future studies, but two likely reasons stem from wind behavior around the form and the model's condition. Figure 10 is the total base moment diagram for the tapering modification. In this figure, the general trend of the base moment is also decreasing from -3 to 8 degrees of tapering.

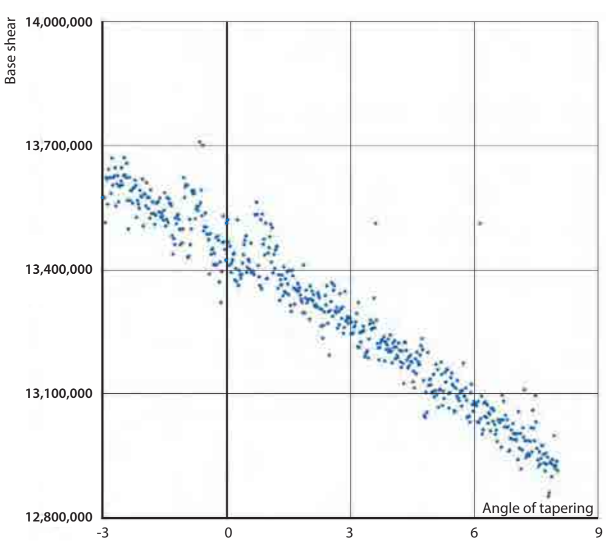

Figure 9. Base shear diagram with various tapering angle modifications.

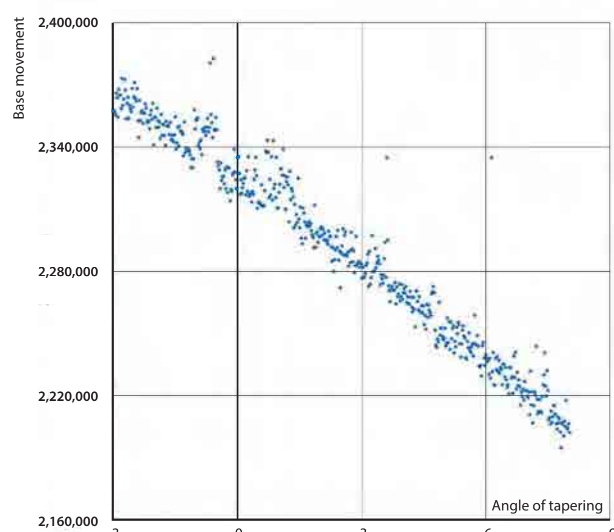

Figure 10. Base moment diagram with various tapering angle modifications.

Based on Figure 10, it can be deduced that increasing the tapering angle (from negative to positive) can reduce the total base moment resulting from the along-wind effect. In this figure, there are also some unexpected outlier results related to shear forces. Although the full explanation is outside the scope of this experiment, it is likely the wind behavior and the model's condition are the causes in this case as well.

Considering framed tube and diagrid systems for structural results

In the following, the weight of the exterior structure of two systems, frame tube and diagrid, are shown. Because the total gross area of all the models is the same, the interior structure for resisting gravity loads is also the same and can thus be ignored as a factor. Therefore, the structural weight shown here is only that of the exterior structural system of the models needed to resist lateral wind load.

In Figure 11, it can be seen that by increasing the tapering angle, the weight of the wind-resisting framed tube structure decreases on a considerable gradient; in other words, the efficiency is increased by increasing the tapering angle. Also considerable: the minimum weight for 8 degrees of tapering is around 27.7 million kilograms and the maximum weight for -2.8 degrees of tapering is around 41.7 million kilograms. The difference between the maximum and minimum in the framed tube system is around 14 million kilograms.

In Figure 11, there are several outlier results. These are likely due to the optimization algorithm of the SAP2000 choosing the most optimal section of the elements, although there may not be enough parameters to make a sufficiently precise model for this purpose in SAP2000. Another likely cause is the variation of the steel sections considered for this research. This can be studied in future research as well.

Before discussing the diagrid system, there is a very important point that has to be considered: in this experiment all the horizontal and vertical elements are eliminated, since the diagrid system is defined as containing only diagonal elements. In practice, beams cannot be ignored because they carry the floor systems. The average weight of the beams has to be added to the weight of the diagrid structure for comparing the results fairly; however, beams are not considered part of an exterior structural system, the subject of this test.

The first important point about the weight of the diagrid structure (see Figure 12) is the close variation range of the results. The range is between around 26.5 million kilograms at -2.5 degrees and 25.7 million kilograms for 0 degrees of tapering; the difference is around 0.8 million kg. This finding indicates that applying the diagrid system does not considerably affect rectangular base models with tapering modifications.

For greater and more realistic understanding, the weight of the structure per unit area (m^2) is presented in Figure 12. The total gross area of the models of this research is 368,640 square meters

Then, the total structural weight divided by this number presents the weight of the lateral load-resisting structure needed per unit of area in the modeled buildings.

Again, in diagrid systems, the weight of the beams per unit of area has to be added, because the diagrid system in this research does not have any horizontal or vertical elements. The average weight of the gravity-load carrying beams has to be added to the weight of the pure diagrid system, which weighs around 26.8 kg/m^2

Figure 13 illustrates that, as the weight of the framed tube system decreases by increasing the tapering angle, the efficiency is increased rapidly (regarding the slope of the diagram). Diagrid systems have no sensitivity to this particular base plan shape, form, and tapering modification when compared to the framed tube system. Considering the estimated weight of the

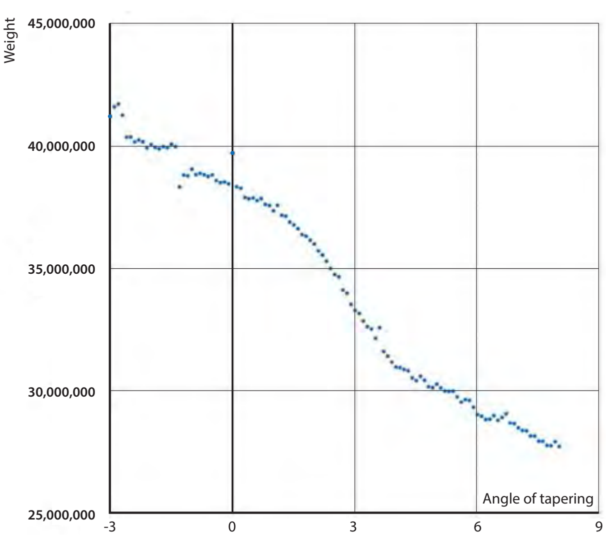

Figure 11. The total structural weight (kg) of the framed tube for various tapering modifications.

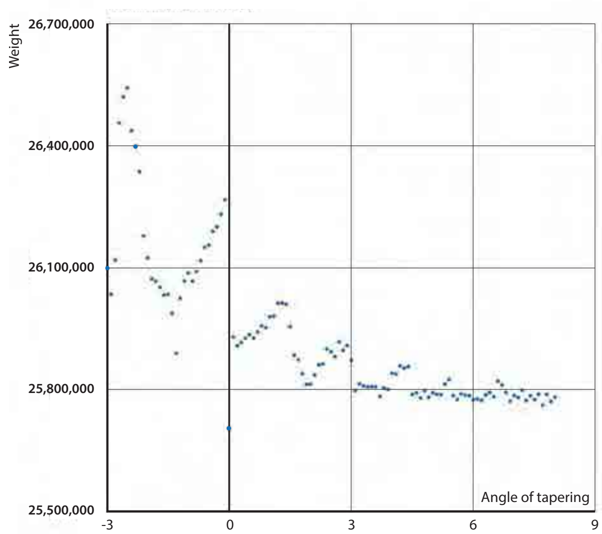

Figure 12. The total structural weight (kg) of the diagrid systems for various tapering modifications.

diagrid system with beams, this solution can be the more efficient system for models with less than three degrees of tapering, but not for all angles.

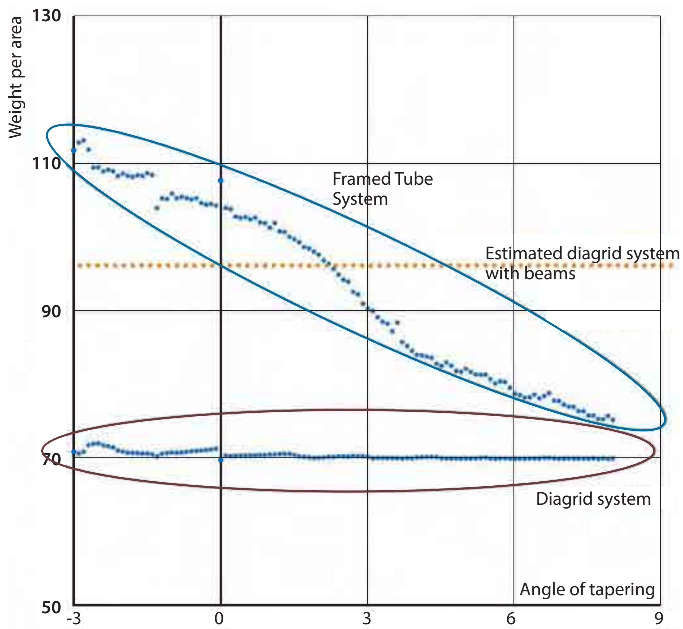

Figure 13. The exterior structural weight of frame tube and diagrid systems per unit of area (kg/m²).

Research Scope and Limitations

Undoubtedly, in this research there are some limitations:

1. The base model of this research is a 90-story building, 360 meters tall, and 64 meters wide, with a fixed height and total gross area.
2. The aerodynamic modification tested in this research is limited to tapering. Future research could consider other types of aerodynamic modifications, such as setbacks and twisting.
3. The structural systems are limited to framed tube and diagrid.
4. The model considered in CFD simulation is a 2D model for considering the along-wind effect. This can be progressed by considering across-wind effect to see the dynamic and aerodynamic response and analysis. With the tools available to the researchers, conducting a 3D CFD simulation to evaluate across- and along-wind effects would be too time-consuming and inefficient.
5. In this research, the efficiency of the structure of the models is judged based solely on the weight of the structure, although many other parameters, such as constructability, durability, and detailing have to be considered in practice.

Achievements and Recommendations

This research shows that architectural strategies (aerodynamic/geometric modifications) and structural strategies (lateral-load-based structural systems) have to be considered together, not individually, from the early stages of tall building design. This project, along with all interdisciplinary research, shows the effect of good coordination between different realms of science and building technology to increase the efficiency of tall buildings in the future. ■

Unless otherwise noted, all image credits in this paper are to authors.

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