Design and Construction of Steel Diagrid Structures

K. Moon
School of Architecture, Yale University, New Haven, USA

ABSTRACT: The diagrid structural system has been widely used for recent tall buildings due to the structural efficiency and aesthetic potential provided by the unique geometric configuration of the system. This paper presents a stiffness-based design methodology for determining preliminary member sizes of steel diagrid structures for tall buildings. The methodology is applied to diagrids of various heights and grid geometries to determine the optimal grid configuration of the diagrid structure within a certain height range. Constructability is a serious issue in diagrid structures because the nodes of diagrids are more complicated than those of conventional orthogonal structures. This paper also presents various strategies to improve constructability of diagrids through prefabrication of the nodes.

1 INTRODUCTION

Since the application of the diagrid structural system for the 30 St. Mary Axe in London and the Hearst Headquarters in New York (Figure 1) both by Norman Foster, it has been widely used for major tall buildings worldwide. The Guangzhou International Financial Center designed by Wilkinson Eyre has been topped out at the height of 437 meters, and the Lotte Super Tower designed by Skidmore, Owings and Merrill will soar into the skyline of Seoul with its height of 555 meters. Today's prevalent use of diagrids in tall buildings is due to their structural efficiency and aesthetic potential. For a very tall building, its structural design is generally governed by its lateral stiffness. Compared to conventional orthogonal structures for tall buildings such as framed tubes, diagrid structures carry lateral wind loads much more efficiently by their diagonal members' axial action.

Another structural system having similar structural efficiency to diagrids is the braced tube developed for tall buildings in the late 1960s. However, today's architects have been losing interest in aesthetic expressions provided by conventional braced tubes composed of orthogonal members and large diagonals because they always seek something new and different. Diagrid structures providing great structural efficiency without vertical columns have also opened new aesthetic potential for tall building architecture. With their distinguished compositional characteristic, diagrid structures are often strongly expressed on the building facades, making them accentuating elements in the existing orthogonal urban context.

This paper presents a stiffness-based design methodology for steel diagrid structural systems for tall buildings. With the rapid advancement of materials science and consequently produced higher strength materials, building structures are more often governed by stiffness requirements because of the lag in material stiffness versus material strength. Different from conventional design methodologies primarily based on strength, the stiffness-based design methodology presented here is based on the structure's optimal deformation mode, which is dependant upon the height-to-width aspect ratio and grid geometry of the structure.

Construction of diagrids is more challenging compared to conventional structural systems for tall buildings because the system is relatively new and the joints of diagrid structures are more complicated than those of conventional orthogonal structures. This paper also presents various strategies to enhance constructability of diagrid structural systems.

Figure 1. Hearst Headquarters, New York (Courtesy of Adam Gimpert).

2 STIFFNESS-BASED DESIGN OF STEEL DIAGRID STRUCTURES

2.1 *Design methodology*

A diagrid structure is modeled as a vertical cantilever beam on the ground, and subdivided longitudinally into modules according to the repetitive diagrid pattern. Each module is defined by a single level of diagrids that extend over multiple stories. Figure 2 illustrates the case of a 6-story module. Depending upon the direction of loading, the faces act as either web planes (i.e., planes parallel to wind) or flange planes (i.e., planes perpendicular to wind). The diagonal members are assumed to be pin-ended, and therefore resist the transverse shear and moment through axial action only. With this idealization, the design problem reduces to determining the cross-sectional area of typical web and flange members for each module. Following the design methodology developed by Moon et al. (2007), member sizes for the modules can be computed using Equations (1) and (2) customized for each design case.

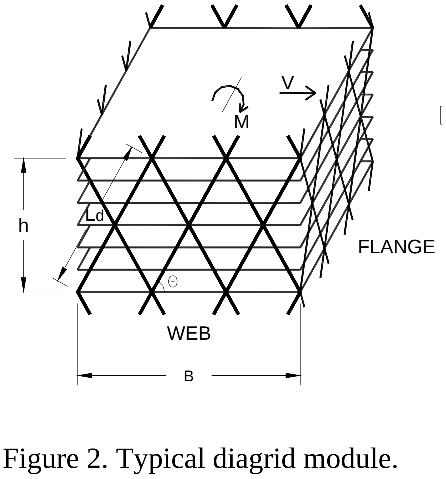


Figure 2. Typical diagrid module.

$$A_{d,w} = \frac{VL_d}{2N_{d,w}E_d h\gamma \cos^2 \theta} \tag{1}$$

$$A_{d,f} = \frac{2ML_d}{(N_{d,f} + \delta)B^2 E_d \chi h \sin^2 \theta} \tag{2}$$

$A_{d,w}$: Area of Each Diagonal on the Web
$A_{d,f}$: Area of Each Diagonal on the Flange
V: Shear Force
M: Moment
L_d: Length of Diagonal
E_d: Modulus of Elasticity of Steel
θ: Angle of Diagonal Member
γ : Transverse Shear Strain
χ : Curvature
$N_{d,w}$: Number of Diagonals on Each Web Plane
$N_{d,f}$: Number of Diagonals on Each Flange Plane
δ: Contribution of Web Diagonals for Bending Rigidity
B: Building Width in the Direction of Applied Force

Optimal stiffness-based design corresponds to a state of uniform shear and bending deformation under the design loading. Uniform deformation states are possible only for statically determinate structures. Tall building structures can be modeled as vertical cantilever beams on the ground, and uniform deformation can be achieved for these structures (Connor, 2003). Then, the deflection at the top, $u(H)$, is given by

$$u(H) = \gamma^* H + \frac{\chi^* H^2}{2} . \tag{3}$$

H: Building Height
γ^* : Desired Uniform Transverse Shear Strain
χ^* : Desired Uniform Curvature

The design begins by specifying the desired bending deformation and shear deformation of the structure. In order to specify the relative contribution of shear versus bending deformation, a dimensionless factor ‘s’, which is equal to the ratio of the displacement at the top of the structure due to bending and the displacement due to shear, is introduced.

$$s = \left(\frac{\chi^* H^2}{2} \right) / \left(\gamma^* H \right) = \frac{H\chi^*}{2\gamma^*} . \tag{4}$$

The maximum allowable displacement, one of the most important stiffness-based design parameters for tall buildings, is usually expressed as a fraction of the total building height.

$$u(H) = \frac{H}{\alpha} \tag{5}$$

Noting equations (3) and (4), equation (5) expands to

$$u(H) = (1+s)\gamma^* H \tag{6}$$

Since, determination of a value for α, which is generally in the neighborhood of 500, is an engineering decision, it remains to establish a value for ‘s.’ Then, the design of diagonals in each module can be performed using Equations (1) and (2) customized for each design case. The following section investigates the impacts of different ‘s’ value selections toward the optimal stiffness-based design, which uses the least amount of material to meet the design requirements. Further, diagrids of different height-to-width aspect ratios are designed with various grid geometries to determine the optimum grid configuration of the system depending on its aspect ratio.

2.2 *Design studies*

The stiffness-based design methodology is applied to a set of diagrid structures, 40, 50, 60, 70 and 80 stories tall, with height-to-width aspect ratios ranging from 4.3 to 8.7. The diagrid structure of each story height is designed with diagonals of various uniform angles as well as diagonals of gradually changing angles over the building height in order to determine the optimal grid geometry of the structure within a certain height range. The building’s typical plan dimensions are 36 x 36 meters with typical story heights of 3.9 meters. The structures are assumed to be in New York. Based on the ASCE/SEI 7-05 Minimum Design Loads for Buildings and Other Structures, the basic wind speed in New York is 110 mph.

Member sizes were generated to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. Regarding the uniform angle diagrids, preliminary studies indicate that the 6-story module having an angle of 63 degrees (Fig. 2) produces the most efficient design for the 40- and 50-story diagrids, while the 8-story module having an angle of 69 degrees produces the most efficient design for the 60-sory and taller diagrids.

As an example design, profiles of the required member sizes for the typical diagonals in the web and flange planes for the 60-story diagrid structure with diagonals placed at a uniform angle of 69 degrees (Figure 3-a) are plotted with s = 4 in Figure 4-a. Since the wind can blow in either direction, the role of a plane can be either a flange or a web. The building considered here has a square plan and the preliminary design value for the module is taken as the larger of the two values. In order to produce the most efficient design, ‘s’ value should be selected so that the bending deformation requirement governs for approximately the lower half portion of the building and the shear deformation requirement for the upper half. Steel usage for the diagonals in this design case is summarized in Table 1. The study is repeated for the 60-story diagrids with varying angle diagonals shown in Figure 3-b. Member sizes and required steel tonnage in this case are shown in Figure 4-b and Table 1. For the 60-story diagrids, it was found that the uniform angle configuration produces more efficient design than the varying angle configuration, and this is also true for the 40- and 50-story diagrids. This is because the negative effect of the reduced shear rigidity caused by the steeper angle at lower levels of the structure is greater than the positive effect of the increased bending rigidity up to the 60-story diagrid structures studied here.

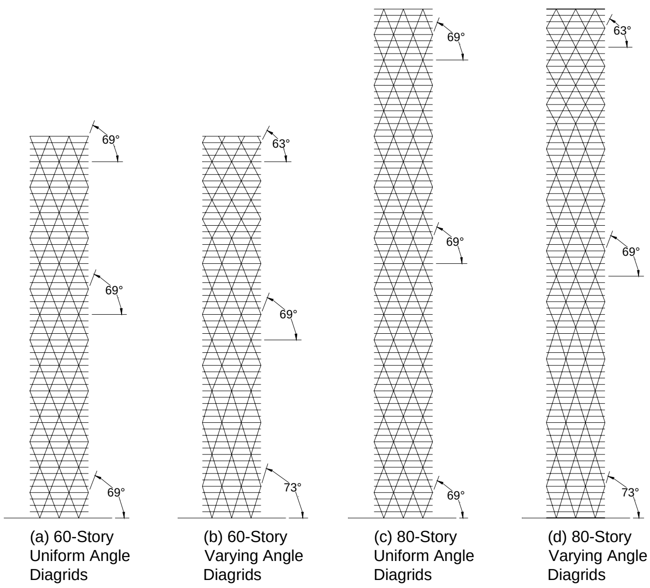
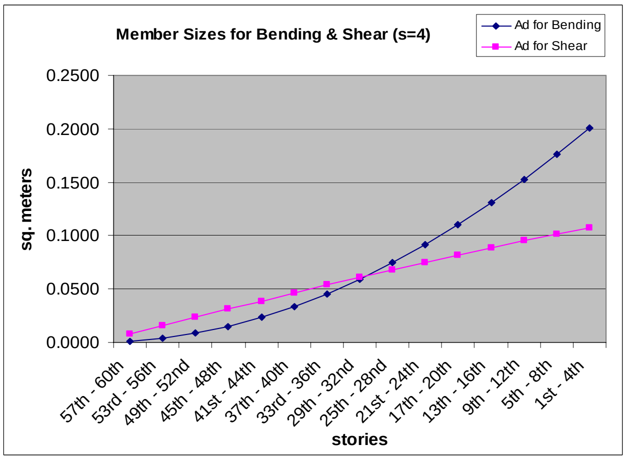
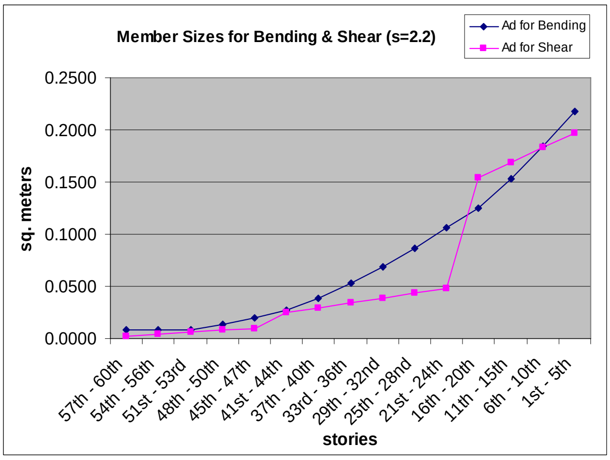


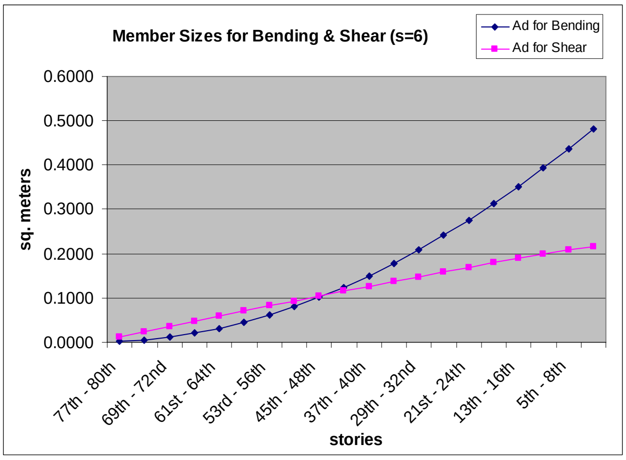
Figure 3. 60- and 80-story diagrid structures with diagonals placed at uniform and varying angles.



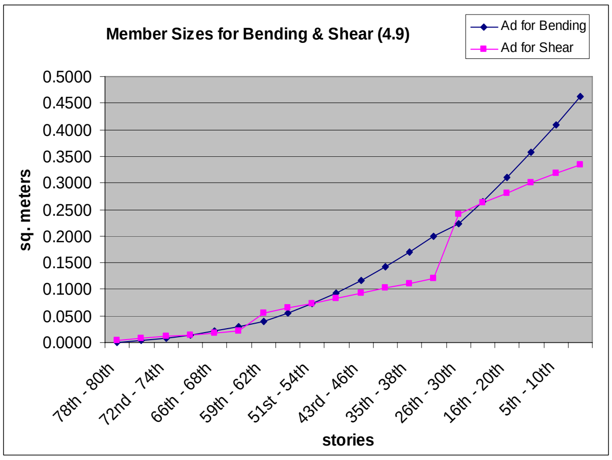
(a) 60-story uniform angle diagrids



(b) 60-story varying angle diagrids



(c) 80-story uniform angle diagrids



(d) 80-story varying angle diagrids

Figure 4. Stiffness-based design for the 60- and 80-story diagrid structures with uniform and varying angles.

Table 1. Structural efficiency comparison between the uniform and varying angle diagrids of various heights

Diagrid Height	Height/Width	Angles Configuration	Steel Mass (Ton)
60 Stories	6.5	Uniform Angle (69 degrees)	3820
		Varying Angles (73, 69 & 63 degrees)	4104
80 Stories	8.7	Uniform Angle (69 degrees)	15611
		Varying Angles (73, 69 & 63 degrees)	11574

However, this is no longer true for the 70- and 80-story diagrid structures. For the diagrid structures, with height-to-width aspect ratios bigger than about 7, gradually changing diagrid angles with the uniform optimal angle as a median angle value produces more efficient design than the uniform angle design cases. The results of the comparative design studies with the 80-story diagrids shown in Figures 3-c and 3-d are presented in Figures 4-c and 4-d as well as in Table 1. Unlike the 40-, 50- and 60-story design cases, the positive effect of the increased bending rigidity caused by the steeper angle at lower levels of the structure is greater than the negative effect of the reduced shear rigidity in the 70-, and 80-story structures. This is because taller buildings behave more like bending beams and shorter buildings behave more like shear beams (Moon, 2008).

Based on the design studies, it is suggested to use a varying angle diagrid structure for a very tall building with its aspect ratio bigger than about 7 as is the case with the Lotte Super Tower in Seoul, and a uniform angle diagrid for a tall building with its aspect ratio smaller than about 7 as is the case with the Hearst Tower in New York, to save structural materials and, in turn, to create more sustainable built environments. Certainly, the most efficient structural solution may not always best satisfy other design requirements. Integrated design approach, which considers every aspect of design holistically, should be appreciated to reach the final design decision.

3 CONSTRUCTION OF STEEL DIAGRID STRUCTURES

3.1 *Node construction for diagrid structures*

Constructability is a serious issue in diagrid structures because the joints of diagrid structures are more complicated and tend to be more expensive than those of conventional orthogonal structures. In order to reduce jobsite work, prefabrication of nodal elements is essential. Due to the triangular configuration of the diagrid structural system, rigid connections are not necessary at the nodes, and pin connections using bolts can be made more conveniently at the jobsite. If considerately designed using appropriate prefabrication strategy, constructability will not be such a limiting factor of the diagrid structures.

Prefabrication of diagrid nodes for conventional rectangular shape buildings can be done relatively easily and economically because many nodes of the same configuration are required in this case. The Hearst Headquarters in New York is the typical case. Figure 5 also shows a typical example design done by students at a tall building design studio taught by the author at the University of Illinois at Urbana-Champaign. The diagrid structure is about 100 stories tall and has a rectangular box form, while the actual building space is defined by a complex shape form within the frame of the diagrid structure. Suggested construction of the nodes is shown in Figure 5. The prefabricated nodes are connected to the large built-up diagonal members by bolts at the jobsite.

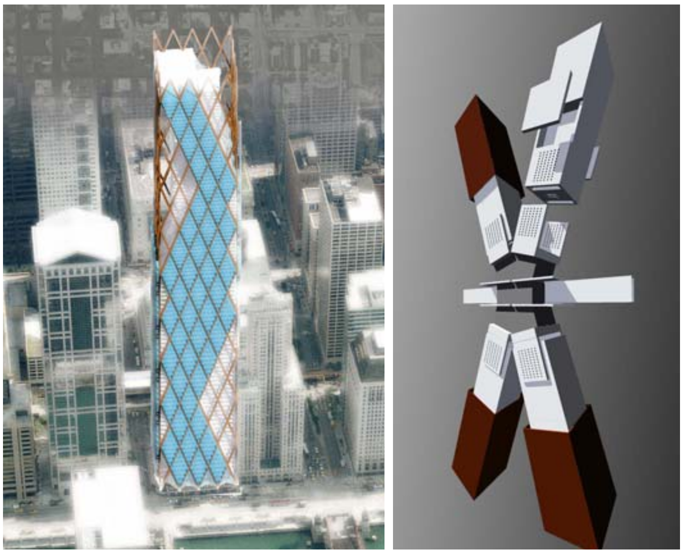


Figure 5. Node detail for a conventional form diagrid building (Courtesy of A. Reyes and S. Mirghaemi).

As building form becomes more irregular, generating appropriate construction modules is critical for better constructability. Though it is possible to produce any complex shape construction module using today's CAD/CAM technology, it is not the most economical solution. Extracting regularity from an irregular building form, and then adjusting the building form following the extracted regularity could be one approach. Another approach could be to make the construction modules relatively regular and design universal connections so that they can accommodate any irregularity. Figure 6 shows a freeform diagrid design example by students at a tall building design studio taught by the author. The structure is also about 100 stories. In order to accommodate angle variations caused by the freeform at the jobsite, the node is composed of two adjustable pin connections joined at 90 degrees. This eliminates the need to produce numerous joints of different configurations. Another similar approach is shown in Figure 7. In this 150 story-tall freeform diagrid structure, cast ball and socket joints are used.

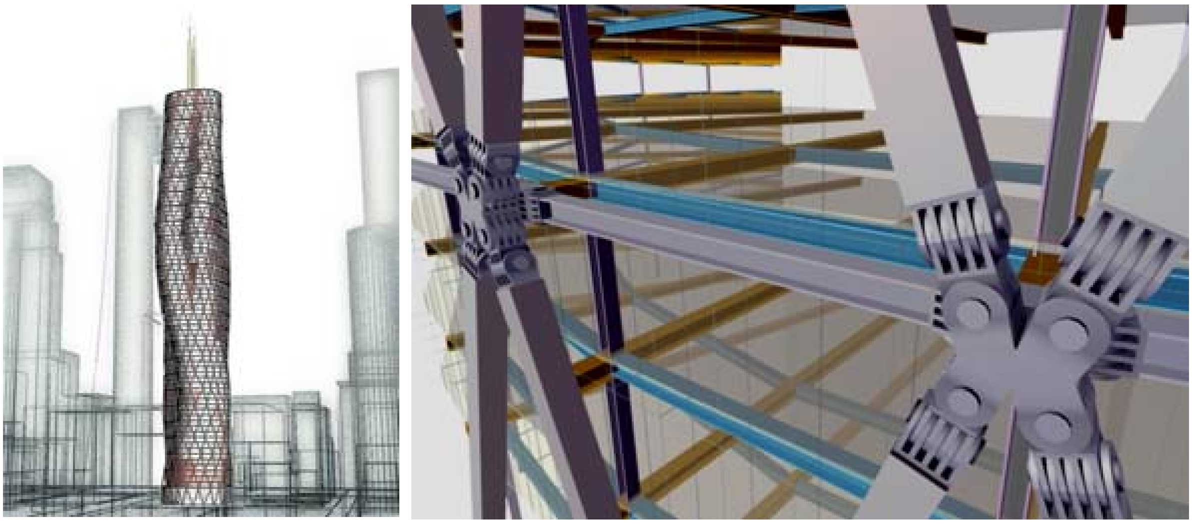


Figure 6. Node detail for a freeform diagrid building (Courtesy of A. Gimpert and N. Georgaklis).

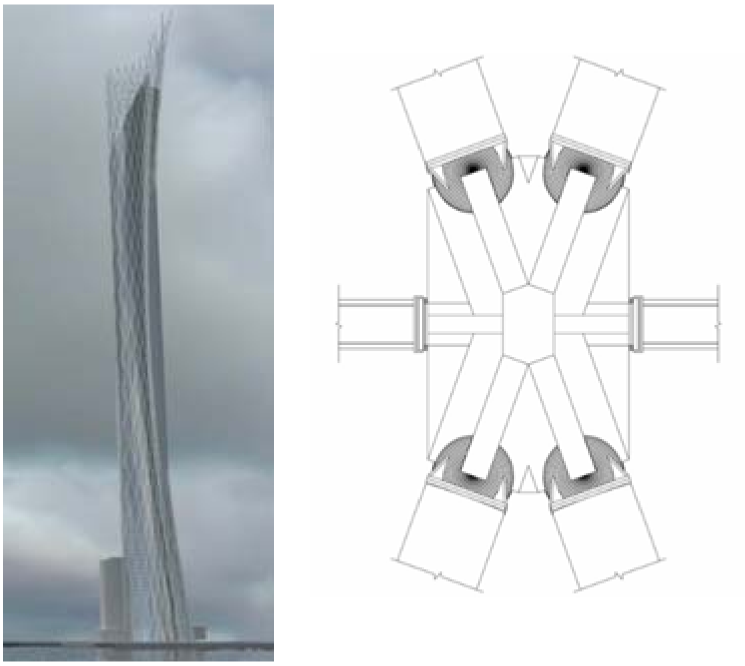


Figure7. Node detail for a freeform diagrid building (Courtesy of W. Godfrey and C. Rocky).

3.2 *Façade construction for diagrid structures*

Different from conventional orthogonal structures, which are generally clad with rectangular shape curtainwall units, diagrid structures are clad with not only rectangular but also triangular, diamond or parallelogram shape curtain wall units. The Hearst Headquarters (Figure 1) uses rectangular shape curtainwalls, while the 30 St. Mary Axe (Figure 8) uses diamond shape curtainwalls. Figure 9 shows a curtainwall unit of parallelogram shape composed of two triangles to clad a diagrid tall building structure.

Curtain walls for building façades should be designed integrally with building structures, which physically support them. It is also very important to note that wind loads are initially applied to the building facades and then transmitted to the structures. Non-orthogonal curtain wall units for diagrid structures require careful design and construction strategies for their enhanced constructability, performance, and aesthetic expression.

Figure 8. Facade construction of the 30 St. Mary Axe (Courtesy of J. Fernandez).

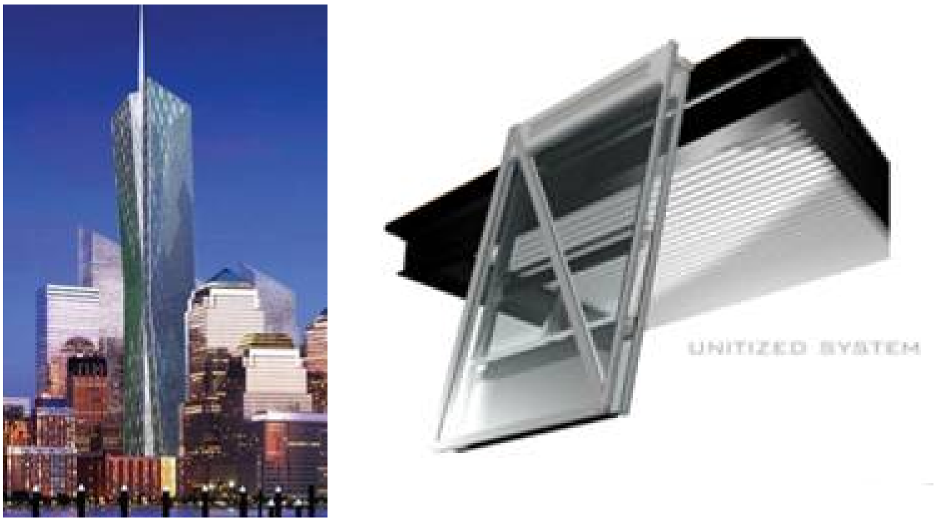


Figure 9. Facade construction of a diagrid tall building (Courtesy of L. Szewczyk and I. Lee).

4 CONCLUSIONS

The diagrid structure has been used prevalently for today's tall buildings worldwide. The unique compositional characteristic of the structure provides great structural efficiency for tall buildings and aesthetic potential in any existing orthogonal urban context. The structural efficiency of diagrids for tall buildings can be maximized by configuring them to have optimum grid geometries. Though the construction of a diagrid structure is challenging due to its complicated nodes, its constructability can be enhanced by appropriate prefabrication methods.

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