Title: Structural Schematic Design of a Tall Building in Asan using the Diagrid System

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Subject: Structural Engineering

Keyword: Structure

Publication Date: 2008

Original Publication: CTBUH 2008 8th World Congress, Dubai

Paper Type: 1. Book chapter/Part chapter
            2. Journal paper
            3. Conference proceeding
            4. Unpublished conference paper
            5. Magazine article
            6. Unpublished

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Biography
JONG SOO KIM

Education:
- B.S. in Architectural Engineering,(1973) Korea University, Seoul
- M.S. in Structural Engineering,(1992) Chung-Ang University, Seoul
- M.D.Paper : A study on the frame system of mid-highrise steel building subjected to the lateral force.

Professional Experience:
With over 30 years of experience in structural engineering, his background is a special combination of practical design experience and high technical contribution to the field. He is a registered Structural Engineer in Korea, as the president of CS Structural Engineering Inc. is responsible for all structural design and production services. He specialized in the analysis and design of high rise buildings and spatial structures. The value engineering gained from his past experience is used in the preliminary stages of project to obtain cost efficient structural designs, including :

- Gwangmyeong Cyclodrome, Seoul
- 2002 Jeonju World Cup Stadium, Jeonju
- Tower Palace I (Tall Apartment), Seoul
- Busan City Hall Tower, Busan
- North-Star Tower, Beijing, China
- Jamsil Galleria Palace (Tall Apartment), Seoul
- Colombo Condominium, Sriranka
- 2002 Gumjung Asian Game Stadium, Busan
- Seocho Acrovista (Tall Apartment), Seoul
- Hyundai Department store, Ulsan
- Hibrand Shopping Complex, Seoul

Design Awards:
1998 POSCO Bronze Prize for Best Steel Structure of The Busan City Hall Tower
2002 POSCO Special Prize for Best Steel Structure of The Jeonju 2002 World Cup Stadium.
2002 KASS’s Ment Award for Outstanding Spatial Project
2002 KSSC’s State-of-the Art Award
2005 KSSC’s Design Award for the Best Steel Geumjung Velodrome of 2002 Asian game
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Abstract
This building, located in Asan, is a tall steel building (stories: B6F~51F, total height: 243.7 m). The building has variations of the plan in each floor, making the exterior of the building curvilinear. This unusual external appearance makes it very distinctive. Comparisons and analyses were performed to select the most efficient structural system and to maximize the uniqueness of the external appearance.

During the concept design, three structural systems, outrigger with belt truss system, diagrid system and super column with super brace system, were proposed. As a result of our study, the diagrid system is recommended for architectural planning, structural efficiency and stability. The diagrid system consists of sloping columns modularized every four stories that act like a braced tube. This system resists lateral forces efficiently by its bending or shear action. Recently the diagrid system has been applied to several tall steel buildings because of its structural efficiency.

More checks and research are required to ensure the stability of the building and efficiency of construction because few have been built. If the diagrid system is selected for this building, it could become a landmark because of its unique external appearance and structural system.

Keywords: diagrid, spiral, tube, landmark

1. Introduction
This project in Asan, Korea (the Penta-Port Project) is a mixed development that consists of the following buildings, as shown in Figure 1.
- Two similar residential towers of 45 stories with six levels of podium car park and two levels of basement
- A residential tower of 66 stories with six levels of retail podium and five levels of basement
- An office tower of 51 stories with seven levels of commercial podium and seven levels of basement
- A department store of 11 stories

Selecting the most efficient structural system for the office tower (story height: 3.5 m, total height: 243.7 m) is the main consideration. To find the optimal system for this office building, a number of stability systems are compared.

2. Comparison of Lateral Resistance Systems
Three stability systems, outrigger with belt truss, diagrid, and super column with super brace system (Figure 3), are compared. Although the outrigger system is the most common for tall buildings, the diagrid system is the most efficient, because the diagrid forms an exterior tube that can maximize the moment arm to resist overturning. Furthermore, the diagrid system has higher torsional rigidity than the others. Applying the diagrid system could make this building a landmark because of its unique structural system and external appearance. The inner view of the diagrid system is shown in Figure 2.

When considering the cost of steel, the cost of the diagrid system is lower than expected because the diagrid maximizes the stiffness of the RC core and this brings the cost down.

Figure 1. Air View of Site

Figure 2. Inner View of Diagrid System

Figure 3. Stability System
3. Diagrid System

3.1 Lateral Load

Comparing the wind and seismic loads, the wind load is double the seismic load. The condition of load is shown in Table 1. In calculating the static seismic load, the response modification factor of 3 was applied for the diagrid system because there is no available response factor for this system in KBC2005 and the ductility of the diagrid system is not clear. This response modification factor makes this system behave safely for seismic loads. In KBC2005, for high-rise buildings with long-period characteristics, the seismic response coefficient is decided by the minimum limit value. The period of this diagrid system is 3.65 s, and with this period the spectrum acceleration is decided by the minimum value, as shown in Figure 4. Therefore R = 3.0 is applied; this value being the most conservative value among the seismic-resisting systems determined in KBC2005.

<table>
<thead>
<tr>
<th>Wind Load</th>
<th>Seismic Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic wind speed</td>
<td>Basic wind speed</td>
</tr>
<tr>
<td>Exposure category</td>
<td>Important factor</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Topographie factor</td>
<td>Important Factor</td>
</tr>
<tr>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 1. Lateral Load

3.2 Lateral Resisting System (RC core + Diagrid)

The structural elements of this diagrid system are illustrated in Figure 7. Recently the diagrid system has been applied to tall buildings because of its structural efficiency. In this building, the main structure is composed of an RC core and the steel diagrid column. (As shown in Figure 5, the podium frame is also one of the lateral resisting elements, but the stiffness ratio of this frame is relatively small.) In this system, the RC core behaves like a cantilever and the diagrid resists shear actions. These two structural elements act together and make the building stiff, as illustrated in Figure 8.

The diagrid is composed of sloping columns modularized in every four stories. It acts as a braced tube as shown in Figure 9. This exterior tube can maximize the moment-resisting capacity of the building. Furthermore, the diagrid structure has much higher torsional rigidity than the others. The diagrid contributes to the stiffness of building by over 40% in each direction. (the RC core contributes the remaining 60%).

Figure 4. Design Spectrum

Figure 5. Structural Element

Figure 6. Stiffness Contributive Ratio

Figure 7. Lateral Resisting Elements

Figure 8. Interaction of Core and Diagrid

Figure 9. Diagrid System 3D Modeling
3.3 Member Design Plan

- **Diagrid Column (Ø800)**

  The diagrid column behaves like a three-dimensional box, resisting both tension and compression. Steel pipe (Ø800) is used and there are three thicknesses of diagrid column members (16, 25, 40t). The stress in the diagrid column is illustrated in Figure 11 under gravity load and in Figure 12 under lateral load.

- **Corner Column (Ø1300)**

  The axial forces transferred from the inclined column to the corner column are concentrated at the corners. Because of this high stress concentration at corners, SRC columns are used, which resist high compressive and eccentric forces. Ø1300 steel pipe is used. Because a circular shape is more efficient for resisting buckling than a square shape, the circular shape is selected for corner columns.

- **Perimeter Girder (H-500 x 200 x 10 x 16)**

  The perimeter girders are designed by considering them as beam–column elements because there are axial forces acting outward induced from the curvature of the exterior shape and additional axial forces generated by the difference in axial forces between upper inclined columns. The perimeter girder must be able to resist bending moments and axial forces from gravity loads and lateral loads.

### Table 2. Member Size

<table>
<thead>
<tr>
<th>Component</th>
<th>Size (mm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>800 (Ø25)</td>
<td></td>
</tr>
<tr>
<td>Corner Column</td>
<td>Ø1300</td>
<td></td>
</tr>
<tr>
<td>Girders</td>
<td>H-500 x 200 x 10</td>
<td></td>
</tr>
</tbody>
</table>

3.4 Node Design

The diagrid segments are planned to minimize onsite butt welding and the welding locations are illustrated in Figure 14. The load path can be divided into two main scenarios, vertical load and horizontal shear (or their combination), as shown in Figure 13. The vertical load will be transferred in the form of an axial load of diagrid members above the node to the gusset plate and stiffeners, then to the diagrid members below the nodes as shown below. The horizontal shear will be in the form of axial loads in the diagrid members above the node with one in compression and one in tension to the gusset plate and stiffeners. The force will then be transferred as a shear force in the gusset plate and then to the other pair of tensile and compressive forces on the diagrid members below the node. From this load path, the shear force at the location of bolt connections is high under lateral load. Because this may create weak points at the node, particularly during earthquakes, the strength of the bolts will be designed carefully.

Figure 10. Typical Floor 3D Modeling

Figure 11. Stress of Diagrid under Gravity Load

Figure 12. Stress of Diagrid under Lateral Load

Figure 13. Load path at Node

Figure 14. Node Design Plan
(1) Bolt Design
Step 1. Bolt Design: The bolts are designed according to KBC2005 (LSD) and the gravity load, wind load and seismic load are considered.

Step 2. Perimeter Girder Design: Unbalanced loads transferred from the diagrid segment (difference of axial load from each inclined column) must be resisted by the perimeter girder.

Step 3. Diagrid Design at Node: The force at a node will be analyzed by FEM.

(2) Construction Sequence
During construction, the stability in the in-plane direction can be provided by the modules themselves and in the out-of-plane direction can be provided by the tie beams at the node. The temporary restraint to the diagrid and the construction may be minimized. The plan of diagrid segment construction is illustrated in Figure 15 and explained as follows. The process of construction is similar to Swiss Re and an example of diagrid construction (Swiss Re) is illustrated in Figure 16.

☐ in-place steel shop welding
☐ lifting up piece by piece
☐ trial shop assembly of parts with high strength bolts
☐ in-place welding
☐ high strength bolts assembly
☐ setting up perimeter girders

4. Main Points

4.1 Diagrid Efficiency
The overall efficiency (stiffness/weight) of the diagrid depends on the slope of the grid. The slope used in this project, 60°, was decided by the architectural curtain wall design. This slope is similar to the slope of the grid in Swiss Re. Because the efficiency of this slope of grid, 60°, was investigated in this project, we did no additional studies on the slope of the grid.

4.2 Radial Tensile Force at Node Floors
Because the diagrid surface is curved vertically, the load transfer from the diagonal members will create a tendency for horizontal radial deformation at the node where it forms a kink, as shown in Figure 17. This will introduce additional forces to the members attached to it. Depending on the angle between the diagonal members of the diagrid and the magnitude of the axial force, this effect may cause the attached slab to crack. Beams will be stressed because of the attached forces, even under gravity load.

Although the change in curvature of the building is small, if the slab is axially attached to the diagrid without any strengthening measures, the stress induced in localized areas could exceed the tensile capacity of the concrete. This issue is particularly important for seismic design. In the Korean code, which employs the response modification coefficient $R$, the seismic-resisting elements must attain a certain ductility to achieve a particular coefficient.
A concrete slab without strengthening under tension will not provide much ductility. If the slab or ring beams provide restraint to the diagrid and contribute to the stability of the system, the stiffness related to the stress level of the slab must be carefully considered.

There are two ways to tackle this problem.

- The unbalanced forces at the node can be resisted by the hoop effect of ring beams and the diagrid detached from the slab. (Swiss Re, London, UK, 180 m tall).
- The unbalanced forces at the node can be resisted by ring beams and tie beams that tie back to the core wall. Figure 18 shows a structural plan with tie beam and ring beam. (West Tower, Guanzhou, China, 432 m tall).

In this project, ring beams (perimeter girder) and tie girders are planned to tackle this radial tensile force. These members are designed depending on the amount of tensile force at each floor.

4.3 Shear Transfer between Core Wall and Diagrid

For a dual system, there is an interaction between the core wall and the diagrid under lateral load. The shear transfer is usually not very large unless there is a significant change in lateral stiffness of either system. In this building, shear transfers occur at three floors. The shear transfer around elevations +90 m and +132 m are mainly because of the change of member sizes of the diagrid. However, the one at around +43.8 m is caused by the change in shape of the diagonals of the diagrid to vertical columns as illustrated in Figure 19. In the model, a flexible diaphragm was used, and the shear transfer between the core and diagrid became more reasonable. The shear transfer occurs gradually at two floors. Because the shear stiffness of the moment frame below is relatively small, most of the force would transfer to the core through the floor diaphragm. For more reliable force transfer, we plan to add horizontal bracing; a 3D model of bracing at the transfer floor is illustrated in Figure 20.

4.4 Diagrid Node Offset

Some of the nodes of the perimeter diagrid are found to be eccentric, as shown in Figure 21. This may reduce the stiffness of the diagrid because of the additional bending and shear deformation at these joints. Another problem could be the strength considerations. Because the offset is always at the corner columns, it introduces additional forces to the columns from the other diagonal members and induces high stress concentrations at the corner columns. This is particularly undesirable for seismic design. If plastic hinges form at the corner columns because of high demand–capacity ratio, “strong column, weak beam” cannot be guaranteed. Therefore, strengthening of these parts is required if eccentric connections cannot be avoided.
4.5 Human Comfort under Wind

Because this building is slender (slenderness ratio 6.0), human comfort under wind is an issue in schematic design checking the acceleration with NBCC.

As a result of wind tunnel tests (Chonbuk National University, March–May, 2007; the experimental model is shown in Figure 23), the maximum peak resultant acceleration is measured to 22 m\(\text{g}\), which exceeds the allowable peak resultant acceleration of 10–15 m\(\text{g}\). Figure 24 shows the maximum peak resultant acceleration. After completion of construction, the wind tunnel test will be confirmed by measuring the dynamic properties of this building. If the results of the wind tunnel test still do not satisfy the criteria, additional damping devices will be installed.

5. Conclusions

(1) The diagrid system is the most efficient structural system because the diagrid forms an exterior tube with much higher torsional rigidity than other systems.
(2) The diagrid segments are planned to minimize onsite butt welds and the bolts connecting the diagrid and perimeter girder are designed strongly.
(3) Ring beams (perimeter girder) and tie beams are planned to tackle the radial tensile force at node floors.
(4) For more reliable force transfer, horizontal bracing is planned where shear transfers occur because of the change in shape of the diagonals of the diagrid to vertical columns.
(5) Strengthening is required at some of the nodes where eccentric connection cannot be avoided.
(6) Depending on the results of wind tunnel tests, additional damping devices may be installed.

Further Study

(1) We plan to develop a construction method for node joints of the diagrid column for stability and constructability.
(2) We plan to perform experimental and finite element analyses of node joints in the diagrid column and to check the manufacture and construction of elements by forming a consortium of steel construction company, special research institute and structural engineers.

References