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Challenges and Opportunities for the Structural Design of the 123-Story Jamsil Lotte World Tower

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Abstract

The Jamsil Lotte World Tower, a high-rise component of the 2nd Lotte World Amusement Complex, is being constructed at Jamsil, Seoul, Korea. This 123-story building with six underground levels consists of a mall, offices, residences, a hotel, and an observation deck at the top of the building. The height is 555m and it will be the tallest building in Korea. The lateral load resisting system is composed of central RC core walls, two sets of steel outriggers, eight RC mega-columns, and two sets of steel belt trusses. The uppermost lantern is made of exposed diagrid frames. A series of wind tunnel tests were conducted and the results were reflected in the structural design. To prevent any structural robustness, important members like spandrel girders, belt trusses, and perimeter columns were designed to have redundancies. Structural Health Monitoring has been performed to assess the current state of system health.

Keywords: Belt Truss; Mega Column; Outriggers; Supertall; Wind Tunnel Testing

Introduction

Recently in Korea, the government has provided assistance on a number of tall building complexes and inner city regeneration efforts. For these projects, many high-rise buildings having 100 to 150 stories were planned in the country, and the Jamsil Lotte World Tower was the first of these to begin construction.

Ever since Korea developed stable economic growth, Korean general contractors have won large-scale contracts from many different countries and employed competitive construction technologies on high-rise buildings overseas. Throughout these experiences, design offices in Korea also have proven their competitive potential in the tall building design industry. The development of high-quality steels by domestic steel manufacturers helped design engineers address many challenges in these tall building projects.

Throughout this paper, challenges and opportunities that were faced when creating the structural design of the Jamsil Lotte World Tower are introduced.

Building Description

The construction site of the 2nd Lotte World Amusement Complex is across from the existing Lotte World theme park. The construction area and gross floor area (GFA) of the 2nd Lotte World Amusement Complex is 87,182.8 m^2 and 810,998 m^2, respectively. It is composed of a high-rise building and several low-rise buildings, and will host a hotel, a shopping mall, offices, residences, culture centers, and conference halls.

The Jamsil Lotte World Tower is a high-rise building in the 2nd Lotte World Amusement Complex and has 123 floors and six underground floors. Within 330,000 m^2 of GFA, it can host a shopping mall, offices, residences, a hotel, and an observation deck at the top of the building. The height of the building is 555 m, and it will be the tallest building in Korea. Reinforced concrete was used for core walls, megacolumns, and hotel slabs. Steel was used for floor beams, deck slabs, outriggers, and belt trusses.

Owners of the property are Lotte Cooperation, Lotte Shopping Co., Ltd., and Lotte Hotel Co., Ltd. and Lotte Engineering & Construction Co., Ltd. is the general contractor. Schematic design (SD) of the Jamsil Lotte World Tower was started in May, 2009, and the design development (DD) stage was completed in December 2011. The final stage of construction documentation (CD) was completed in December 2012. Currently, construction is in progress.

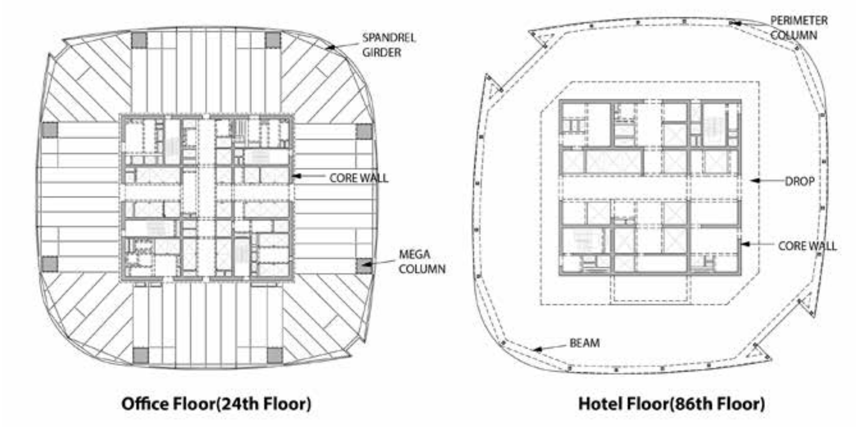

Figure 1. Typical floor plans (Source: Chang Minwoo Structural Consultants)

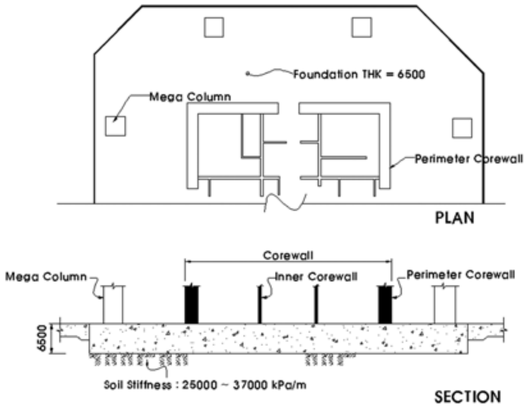

Figure 3. Typical floor plans
(Source: Chang Minwoo Structural Consultants)

Structural Plan

The 2nd to 86th floors of the tower, which will be used for a shopping mall, offices, and residences, are made of steel beams and deck slabs. The hotel floors over the 86th floor consist of 225–300 mm-thick flat slabs (see Figure 1). The ground level and the underground floors are made of reinforced concrete. The lateral load resisting system is composed of central RC core walls, two sets of steel outriggers, eight RC mega-columns, and two sets of steel belt trusses (see Figure 2). The uppermost lantern is made of diagrid frames which are exposed on the exterior.

The concrete strength of the vertical structural members including core walls and mega-columns varies from 40 to 80 MPa, and that of the horizontal members including slabs and beams is 30 MPa, while that of the foundation is 50 MPa. The high strength concrete with a compressive strength greater than 60 MPa is made by the polymix fiber injection method to protect the building from heat explosion. The yield strength (fy) of the rebar is 400 MPa, but when the diameter of the rebar is larger than 25 mm, high strength rebar with 500 or 600 MPa is used.

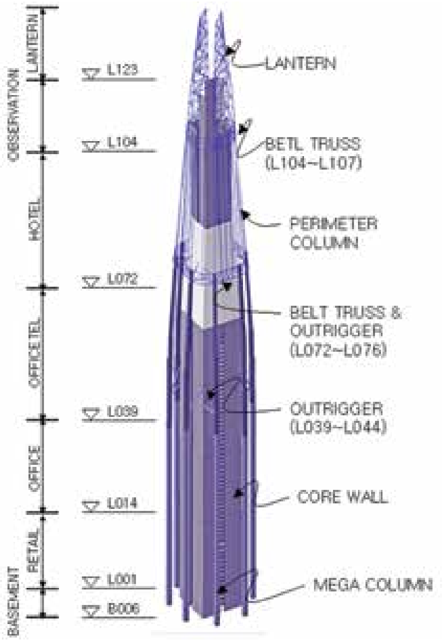

Figure 2. 3D Elevation (Source: Chang Minwoo Structural Consultants)

Most of the steel members have a yield strength between 235 and 440 MPa. High strength steel with a yield strength 650 MPa of is used for the belt trusses, hotel perimeter steel columns, and some parts of the outriggers.

For the floors of the offices and residences, with story heights of 4.5 m and 3.9 m, deck slab thicknesses of 130 mm and 150 mm, and floor steel beam depths of 600 mm and 480 mm were scheduled, respectively. The slabs for the hotel floors, which have story height of 3.6 m, were designed as flat slabs with 500 mm-thick drop panels.

The cross section area of the megacolumn is 3.5m by 3.5m at the bottom (level B6) and it decreases to 2.0 m by 2.0 m at the 66th floor. The thicknesses of perimeter core walls vary from 600 mm to 2,000 mm, while the thicknesses of inner core walls are 300 mm or 500 mm per plan.

The outrigger trusses were designed to be built at two different locations, the 39th–44th floors and the 72nd–76th floors, and the belt trusses are planned to be built at the 72nd–76th floors and the 104th–107th floors. The mat foundation of the tower has a thickness of 6.5 m and an allowable bearing force of 3,000 KPa. In some fault zones and shear zones below the foundation, ground strengthening piles were installed. The structural design of the Jamsil Lotte World Tower was based on the Korean Building Code (KBC2009).

Foundation

According to a geotechnical report, the soil beneath the foundation is composed of soft rocks and hard rocks. Their allowable bearing strength is 3,000 KPa which is enough to support the building weight. However, this area contains fault zones and shear zones that may cause settlement. To prevent the settlement, ground strengthening piles were applied. The piles with 1.0 m diameter were installed using a PRD (Percussion Rotary Drilled) method to prevent the settlement of the mat foundation and uneven settlement under the RC core walls and the megacolumns.

A sand cushion was installed at the upper parts of the piles to separate them from the mat foundation. The 6.5 m-thick mat foundation was designed considering static and dynamic soil springs with the help of soil engineering specialists (see Figure 3). In addition, cool flowing concrete of 50 MPa was used to control hydration heat.

Lateral Load Resisting System

According to design intent, lateral loads on the building are resisted by the RC core walls, outriggers, belt trusses, and megacolumns.

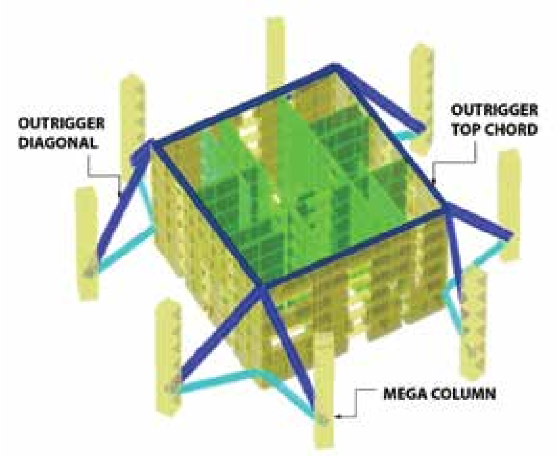

Figure 4. Outrigger truss (L39-44) (Source: Chang Minwoo Structural Consultants)

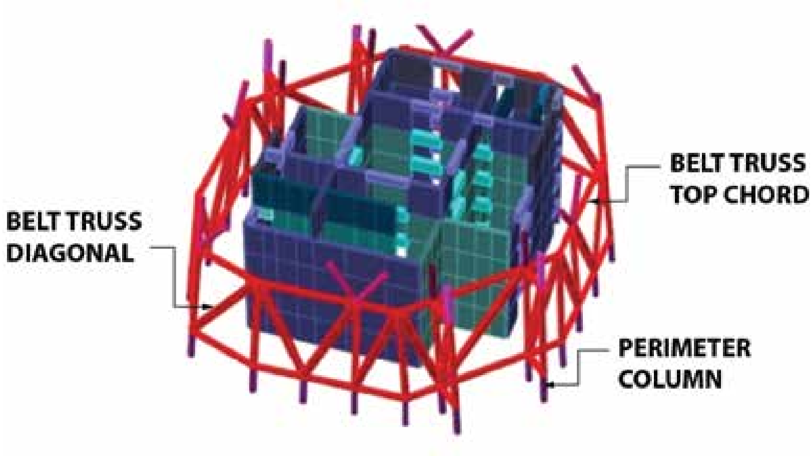

Figure 5. Belt truss (L104-107) (Source: Chang Minwoo Structural Consultants)

During the SD phase, it was originally planned to have three sets of outriggers and six sets of belt trusses, but it was found to be inefficient to have this many sets of outriggers and belt truss in the system. So the plan was changed during the DD phase.

As shown in Table 1, a comparative study of the lateral load resistance ratios of the outriggers, belt trusses, and RC core wall was conducted. As a result of the study, the two sets of outriggers and the two sets of belt trusses were identified as the most optimal solutions for the lateral load resisting system. Perimeter frames of typical floor were also changed to a long span spandrel girder system that connects megacolumns.

The thickness of the perimeter core walls varies from 600 mm to 2,000 mm. The thickness of the cross-shaped inner core walls is 500 mm. The two sets of outriggers are installed at the 39th–44th floors and the 72nd–76th floors (see Figure 4). The contribution of outriggers to control othe lateral displacement is about 29%.

Steel box B-1600 × 500 × 80 × 20 is used for outrigger diagonal members. Since they mainly support axial loads, the web thickness of the steel box was increased to 80 mm and the flange thickness was decreased to 20 mm. For a decision of the thickness, welding workability was considered. The top chord of the outrigger penetrates the RC core wall and reach horizontal truss member on the other side so that horizontal forces in the RC core walls can be easily transferred to the outrigger trusses.

Delay joints are installed to minimize additional member forces caused by differential shortening between the RC core walls and the megacolumns. RC core walls and megacolumns will be connected after completion of the frame construction.

The two sets of belt trusses are placed at the 72nd–76th floors and the 104th–107th floors, of which height is equal to 3 or 4 stories (see Figure 5). The upper belt trusses support the uppermost lantern structures, and the lower belt trusses support the hotel columns between the 76th and 103rd floors. The upper belt trusses contribute to control the lateral displacements. It was proved that the belt truss is more effective than the outrigger truss at that location. The upper chords and the bottom chords of the belt trusses at the 104th floor are steel boxes of B-450 × 400 × 30 × 45, and the diagonal members are B-550 × 400 × 15 × 50. Slabs supported by the outriggers and belt trusses are considered as flexible diaphragms, and the design of these slabs considered in-plane tension, compression, shear force, and out-of-plane force.

	Final Plan	ALT 1	ALT 2	ALT 3	ALT 4
	"OT 2sets BT 2sets"	"OT 3sets BT 6sets"	"OT 2sets BT 6sets"	"OT 3sets BT 5sets"	"OT 3sets BT 6sets"
"Outriggers (OT) location (floor level) "	39, 72	40,72,106	39,72	39,72,106	39,72,106
Belt trusses(BT) location (floor level)	72, 104	11, 021, 40, 59, 74, 106	11, 21, 39, 59, 73, 106	11, 21, 39, 59, 73	73, 106
1st mode period	9.26sec	9.09sec	9.10sec	9.19sec	9.25sec
Max. disp. due to wind	100%	96.30%	97.40%	106.00%	98.90%
Overturning moment ratio of OT+BT	28.50%	30.20%	30.20%	29.90%	28.50%

Table 1. Alternatives for outrigger and belt truss system of Jamsil Lotte World Tower (Source: Chang Minwoo Structural Consultants)

Wind Test	Overturning Moments			Base Shears	
	Mx (N-m)	My (N-m)	Mz (N-m)	Fx (N)	Fy (N)
HFFB	1.94E+10	1.85E+10	1.93E+10	6.55E+07	6.81E+07
Aeroelastic	1.52E+10	1.54E+10	1.93E+10	5.69E+07	5.60E+07

Table 2. Wind tunnel test results (Source: Chang Minwoo Structural Consultants)

Wind Tunnel Test

A series of wind tunnel tests were conducted by Rowan Williams Davies & Irwin (RWDI) Inc. After the 50% SD stage, a high frequency force balance (HFFB) test was conducted, and the analysis was done twice at the end of the SD and after the 60% DD stage. During the 90% DD stage, when most of the dynamic properties were identified, an additional aeroelastic model wind tunnel study was conducted after the 50% SD stage and after the 90% DD stage, respectively (see Figure 6). In addition, wind flow environment tests were conducted to compare wind environments with and without low-rise buildings.

After the tests, it was found that wind loads calculated from the aeroelastic model study were 17–22% lower than that from the HFFB test. And the base shear was also lower than that from the HFFB test by 15% (see Table 2). Response acceleration at the top floor was reduced by about 8%. According to a wind load expert, the aeroelastic results

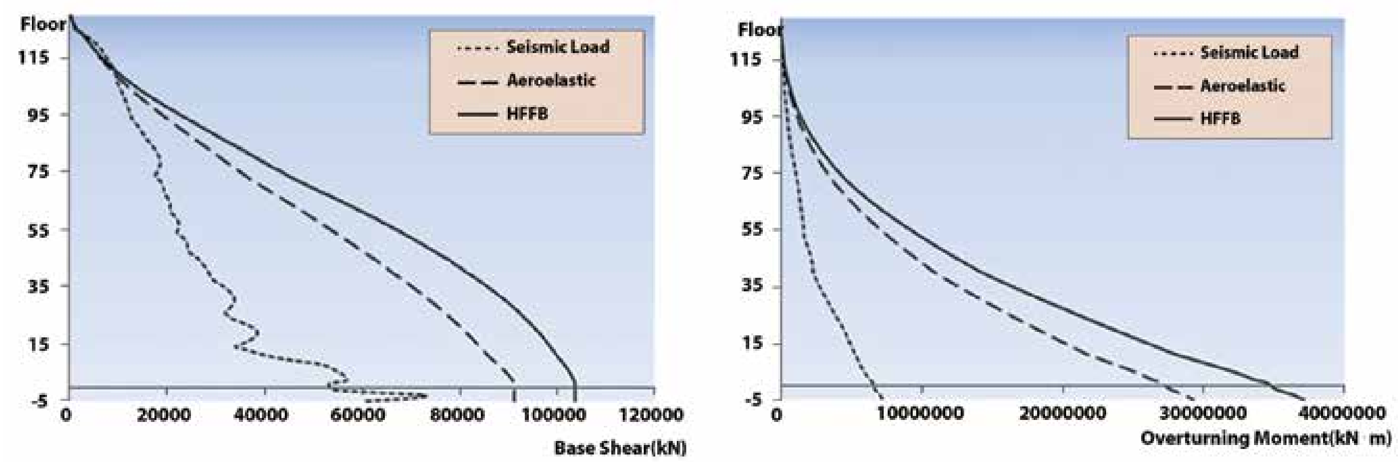

Figure 8. Comparison of wind and seismic loads in terms of Base Shear and overturning moment (Source: Chang Minwoo Structural Consultants)

can be more favorable due to the following reasons: the aeroelastic experiment reflects its aeroelastic effects to the model just like aerodynamic damping effects; a peak factor can be obtained directly from the experiment; some assumptions on the vertical distribution of general wind forces in the wind test were omitted. So, the results of the aeroelastic study are adopted for the structural design.

According to the aeroelastic study, the Jamsil Lotte World Tower satisfies acceleration limits as well as torsional velocity limits recommended by ISO 2007, CTBUH, AIJ, and RWDI (see Figure 7). The response acceleration to the one-year return period wind load at the top of hotel floors (L101) is AIJ H-10, which is far less than the limit, AIJ H-30. This result proves that the structural design of the Jamsil Lotte World Tower guarantees excellent serviceability against wind vibrations.

Figure 6. Aeroelastic model (Source: Chang Minwoo Structural Consultants)

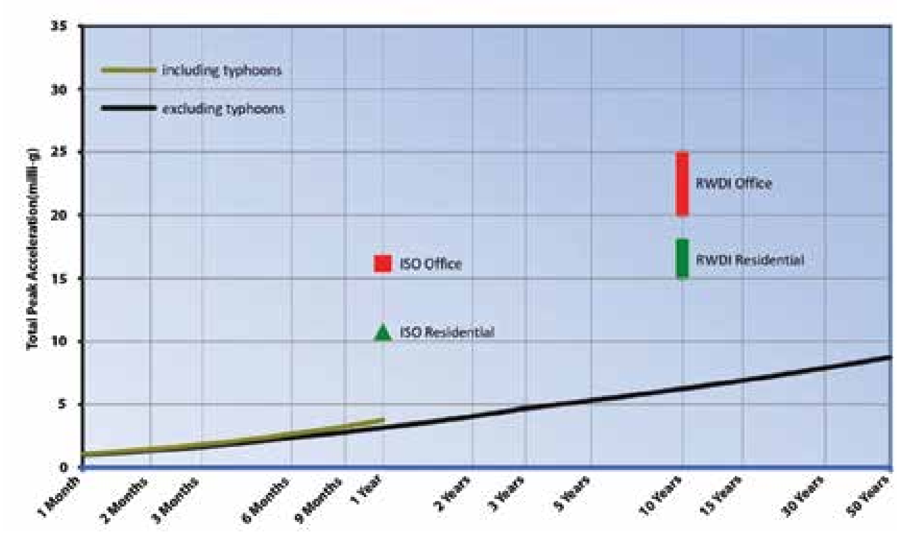

Figure 7. Response acceleration at the top floor of the hotel (Source: Chang Minwoo Structural Consultants)

To calculate seismic loads in Seoul, a seismic numerical coefficient(S) was selected to be 0.176 and response modification coefficient to be 4.0, which are the values that are used for a normal reinforced concrete shear wall system. A series of linear elastic time-history analyses were conducted using three artificial seismic waves. After an evaluation of the seismic load, it was judged that the wind load governs the design of the building except the lanterns. The wind load is 1.52 and 4.04 times larger than the seismic load in terms of base shear and overturning moment, respectively (see Figure 8).

Redundancy

The important members, such as spandrel girders in typical floors, belt trusses, and hotel steel columns, have redundancies

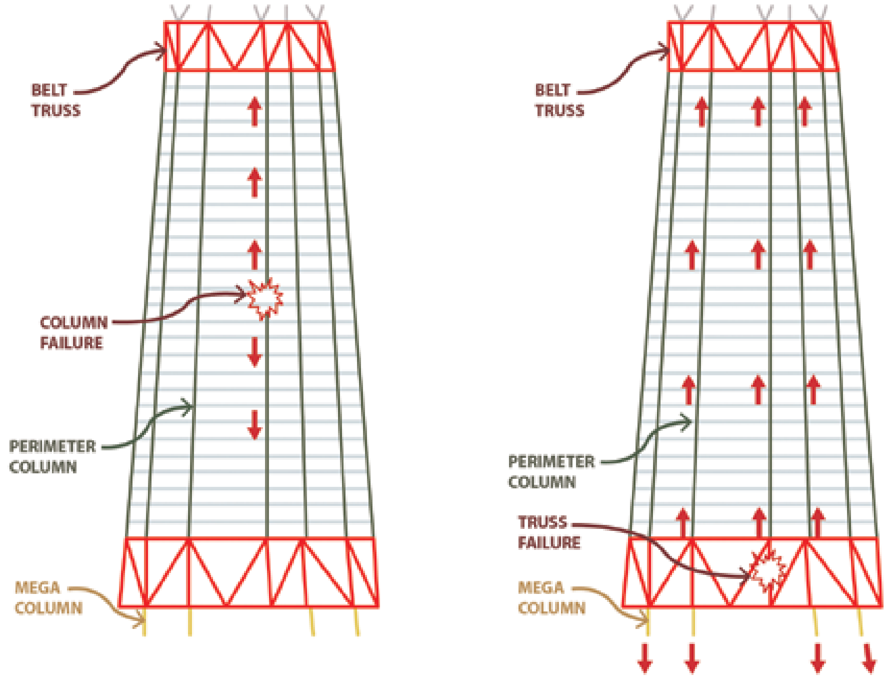

Figure 9. Robustness and redundancy (Source: Chang Minwoo Structural Consultants)

to avoid a sudden collapse when one of these members loses its capacity in case of fire or unexpected impact. The long-span spandrel girders and their connections are designed such that the loss of flexural capability of the girders at any point of span does not result in disproportionate collapse of the floor structures above or below. Also, the belt truss members and the perimeter columns are designed such that the loss of any perimeter column or the loss of any belt truss member does not result in disproportionate collapse of the surrounding structure (see Figure 9).

Serviceability

To check the serviceability against floor vibration, frequency limits and maximum response acceleration recommended by AISC, "floor vibrations due to human activity" were considered. Also, advice from experts were reflected upon. For example, in the fitness area of the Jamsil Lotte World Tower, the stiffness of the floor frame was made to satisfy natural frequency of 9.0 Hz, as recommended by an acoustical expert. The acceleration limits considered in the design are shown in Table 3.

	Vibration limits	Response acceleration limits
Office	3.0 Hz ≤	≤ 0.31 %
Officetel & Hotel	3.0 Hz ≤	≤ 0.15%
Retail	3.0 Hz ≤	≤ 1.50%
Fitness Area	9.0 Hz ≤	≤ 5.00%

Table 2. Acceleration limits by usage (Source: AISC)

Deflection limits are also considered for serviceability. The immediate deflection of steel beams due to live load shall not exceed the lesser of 1/500 of span and 20 mm. The immediate deflections of the spandrel girders supporting curtain walls shall not exceed the lesser of 1/500 of span and 15 mm for live load.

By checking all the limits in addition to those mentioned above, the Jamsil Lotte World Tower satisfies its serviceability limit states.

Connections

The megacolumns and core walls are made of RC, and most of the floor beams, belt trusses, and outrigger trusses are made of steel. Therefore, RC-steel connection details are required to account for constructability, construction periods, and structural safety. To improve constructability and reduce possible delay due to interference between the megacolumns and connections, the spandrel girders and the belt trusses were designed to pass by the megacolumns, rather than penetrate them. However, since this approach has never been used in practice, additional studies were required.

As a cooperative research organization, Seoul National University Integrated Research Institute of Construction and Environment participated in further development and verification of the suggested connection details by conducting theoretical and experimental research. Finally, the research results produced enough confidence for the new RC-steel connection details to be used.

Belt Truss Connection: If the belt trusses supporting the hotel columns are installed along the outside of the megacolumns, the megacolumns can be constructed continuously regardless of the belt truss construction process. As shown in Figure 10, the belt trusses are fabricated through the field welding of pre-assembled trusses with the embedded plates on the outsides of the megacolumns.

To reduce deformation of the 14.4 m-high embedded plates caused by axial loads and to design proper dowel bars, shear transfer bearing plates are needed in every space between dowels. And it was assumed that cracks would occur at the edge of the embedded bearing plates in the mega-column. Therefore, the embedded plate is installed on only one-side of the mega-column but in some floor levels the plate would enclose all four sides of the megacolumn.

Spandrel Girder Connection: The spandrel girders are connected to the outside of the megacolumns just like the belt truss connections (see Figure 11), and additional connections are placed at two sides of the megacolumn. The shear plate is welded on the embedded plate so that it can connect the web of a perimeter beam. The upper flanges of the spandrel girders and megacolumns are connected to fix the

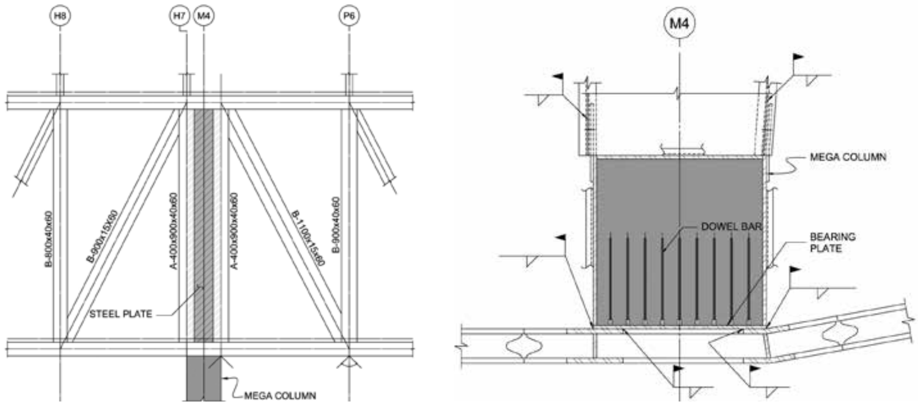

Figure 10. Belt truss & mega-column connection (Source: Chang Minwoo Structural Consultants)

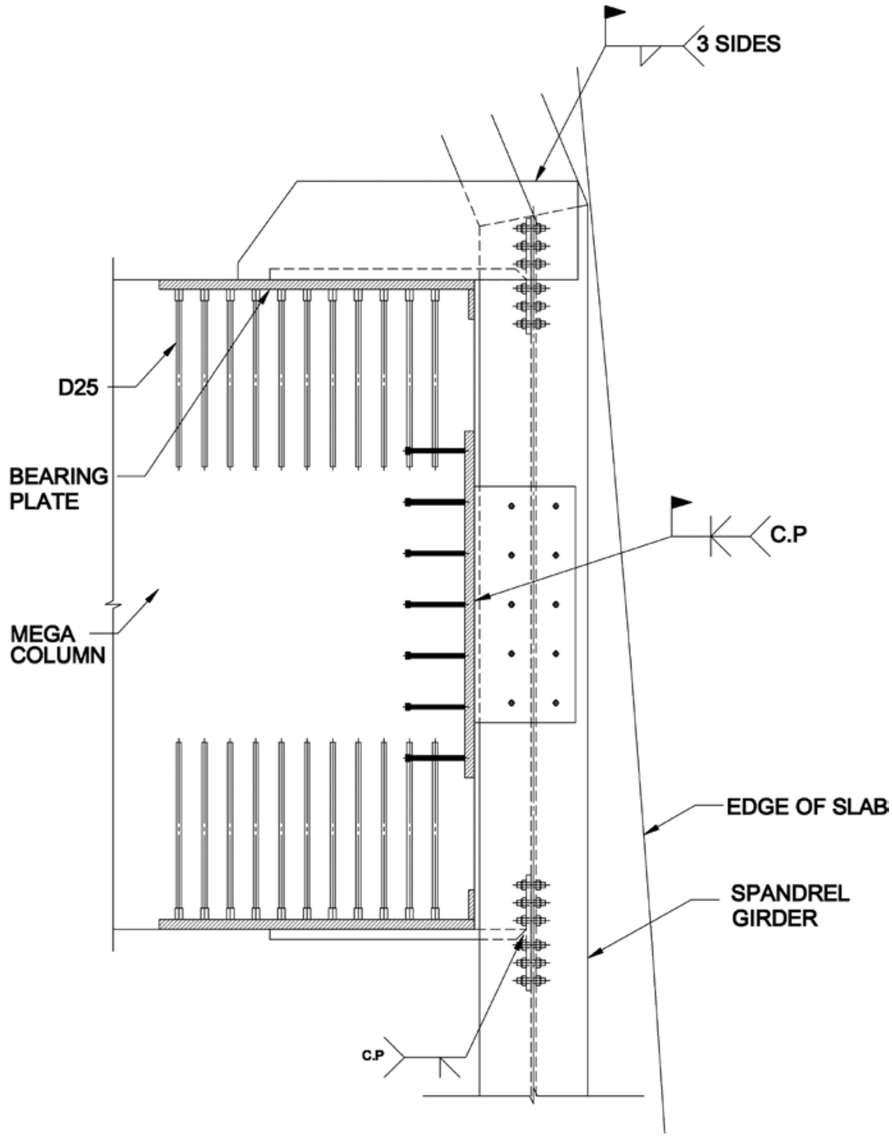

Figure 11. Spandrel girder connection (Source: Chang Minwoo Structural Consultants)

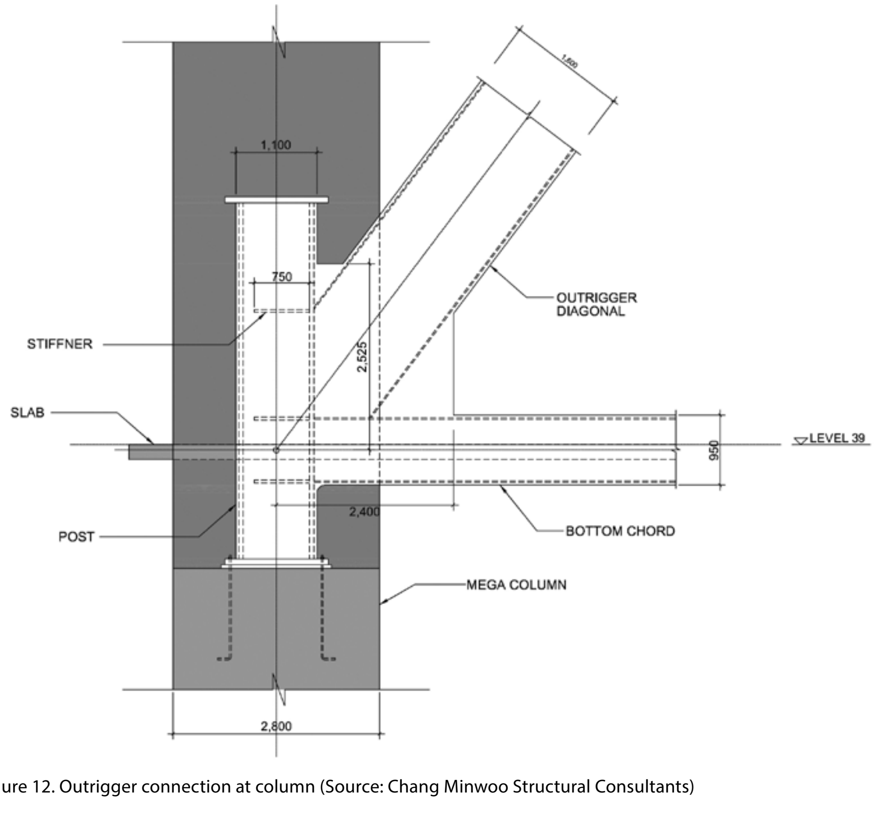

Figure 12. Outrigger connection at column (Source: Chang Minwoo Structural Consultants)

girders during the construction and to brace the megacolumns laterally. Connections at the corner of the megacolumns were designed as reinforcing plates at the top and the bottom flanges of the perimeter girders in the perpendicular direction to prevent the torsional moment caused by the bent connections of the perimeter girder. Just like the belt truss details, bearing plates and dowel bars are planned to be embedded in the megacolumns.

Outrigger Connection: For the design of the connections between the outrigger members and the megacolumns, it was intended that an outrigger diagonal member and a horizontal member be connected at a column-embedded connecting post, as shown in Figure 12. Horizontal forces to the outrigger diagonal member are supported by the bottom chord.

At the connection of the outrigger member and the perimeter core wall, two outrigger members cross each other at a right angle. The upper and the lower flanges of wall-embedded outrigger members are removed to avoid interference with vertical rebar near the corner and to be filled with concrete more densely. At the wall corners, to support vertical force of the outrigger diagonal member, a vertical post is installed at top and bottom of the outrigger member. The top chord supports horizontal forces to the diagonal member.

Application of High-Strength Steel: HSA800

As a value engineering (VE) item, a comparative study on the application of HSA800, the high-strength steel, and S M520 & 570 was conducted for the outriggers, perimeter columns, and belt truss members. It was expected that, by using HSA800, more economical construction can be achieved while providing similar performance of using SM520 and SM570.

The belt truss, perimeter columns, and outriggers were redesigned to use HSA800 in the consideration of progressive collapse or lateral stiffness. Regarding the redesign, the thickness of each member was reduced by a yield strength ratio between SM520 (or 570) and HSA800 so that the stress ratio in the members can be remained. It was confirmed that reduced members using HSA800 can provide similar lateral stiffness. And also it can prevent progressive collapse by checking the natural period of the building and running analytical progressive collapse scenarios.

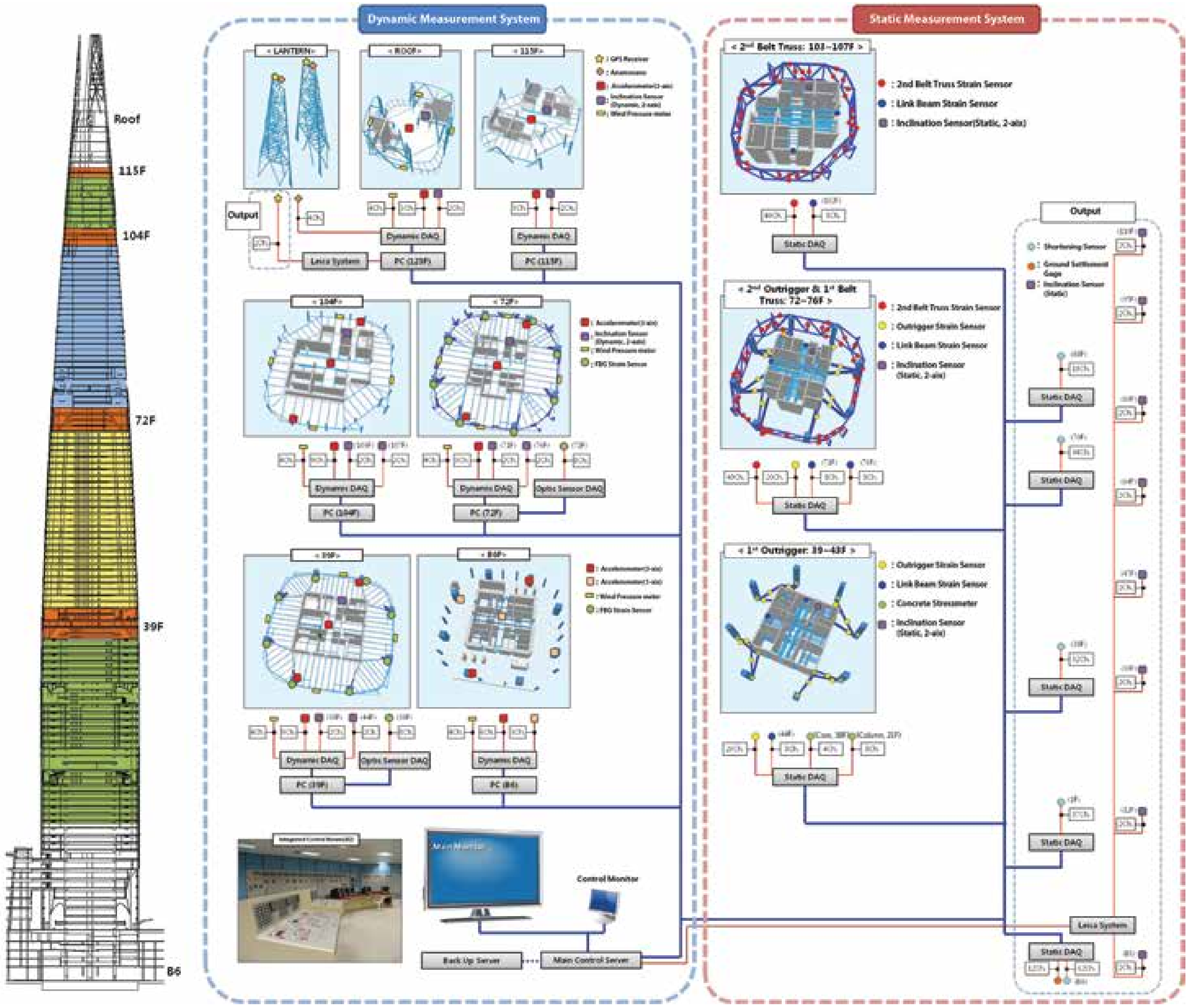

Figure 13. SHM system basic conceptual diagram (Source: Chang Minwoo Structural Consultants)

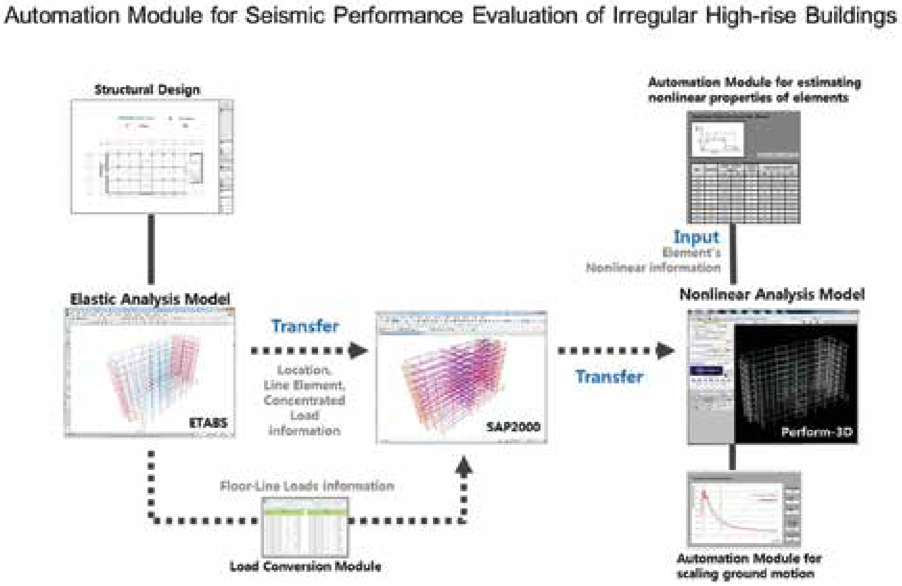

Figure 14. BIM-based modelling transferring process (Source: Chang Minwoo Structural Consultants)

By running the evaluation of total cost for belt trusses, outriggers, and perimeter columns, it was found that two billion won can be saved if HSA800 is used. In addition to savings in the total cost, the usage of HSA800 would improve constructability by allowing a more advanced material lifting operation plan because of reduced member sections.

Structural Health Monitoring

Structural Health Monitoring (SHM) has been performed for the Jamsil Lotte World Tower to meet social demands on the safety and serviceability of the building. Measurement devices for wind loads, stresses, displacements, accelerations, slopes, and field response accelerations are implemented in the Jamsil Lotte World Tower SHM system. The measurements are used to establish the integrated monitoring system (see Figure 13).

Simulation using FEM model is performed to obtain a static pushover, dynamic response, seismic response, wind response analysis.

Linear/nonlinear performance evaluation for a structural dynamic response has been analyzed in order to evaluate acceleration, displacement sensitivity, and stress conditions of the building. For accurate and economic works of creating a nonlinear analysis model, the BIM based modelling transferring process was used. In the process, automation modules for converting loads, estimating nonlinear properties, and scaling ground motion are used to enhance the modelling transformation (see Figure 14). Through the pushover analysis, the relation curve between the force and displacement of structure and the plastic hinge distribution of structure as increasing the displacements are obtained (see Figure 15).

During construction and after the construction completion, natural frequency measurements and structural dynamic responses have been evaluated. By performing comparison analysis between measurements and analysis results, the condition assessment system and the integrated monitoring management system will be developed.

Conclusion

In this paper, challenges and opportunities for the tallest building in Korea were introduced. This building will be the symbol of high technologies that Korean engineers have achieved.

The Ministry of Land, Infrastructure and Transport of Korea has leaded research projects such as "Development of Super Tall Building Design and Engineering Technology" and "Development of Structural Performance Enhancement Technologies for Small-size or Existing Buildings Against Earthquakes and Climate Changes." With this great support from the government, a number of design offices and research institutes could have made outstanding developments in high-rise design technologies. In this project, many remarkable outputs such as the complex-shaped tall building design optimization process and the performance-based seismic design methods were implemented.

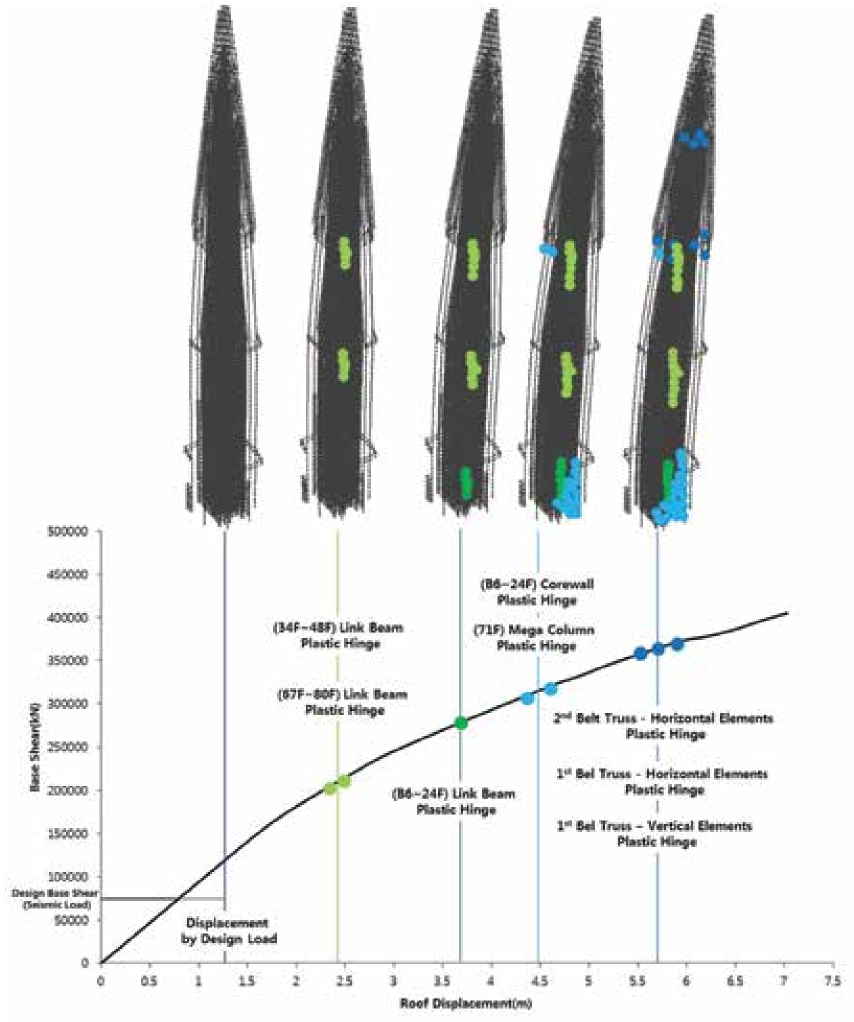

Figure 15. Pushover curve (Source: Chang Minwoo Structural Consultants)

In addition, Korean steel manufacturers have spent a lot of effort on R&D projects to improve the quality of structural steel. They have recently proven that their products show great performance for seismic structures. Consequently, based on stable cooperation between the engineers involved in Korean Society of Steel Construction and the steel suppliers, various high-rise buildings are currently being planned in Korea.

Therefore, by reflecting the design example introduced above and in current practice, it is expected that Korea will foster more experienced engineers and manufacturers with high-technologies and be exceptionally competitive in the steel high-rise design industry.

Acknowledge

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References:

Architectural Institute of Korea (AIK) (2009) **Korean Building Code 2009**, KBC 2009, AIK, Korea.

Kim JH., Kim J., Kim T., Jung Y., Lee J., and Lee Y. (2012) **Structural Design of Lotte Jamsil Super Tall Building**, In Proceedings of 18th congress of International Association of Bridge and Structural Engineers. September, 2012, Korea. pp. 170-172.

Lee D., and Kim T. (2011) **New Steel Structures: Seoul International Finance Center**, Journal of Korean Society of Steel Construction, Vol. 23:2011. p.82.

Kim JK., Kim JH., and Kim J. (2004) **Structural Design of SK Euljiro Headquaters,** Journal of Korean Society of Steel Construction, Vol. 16:2004. pp.56-60.

Kim JH., Jung Y., Kim J., Kim YW., Bahk Y., and Lee J. (2013) **Structural Design of Steel High-Rise Buildings in Korea**, The Pacific Structural Steel Conference (PSSC 2013), Singapore, 11 October 2013.

Lee J., Kim J., and Jung Y. (2014) **Structural Design of Lotte World Tower and Horizontal Strain**, Journal of the Korean Structural Engineers Association, May, 2014, Vol.21, No.3, pp.32-42.